

**TIME DOMAIN ELECTROMAGNETIC SURVEYS
FOR ASSISTING IN DETERMINING THE
GROUNDWATER RESOURCES ON
PROPERTY LOCATED IN THE LAHAINA DISTRICT
ABOVE KAAHAPALI
ISLAND OF MAUI**

Project Number 5156

November 2009

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TABLE OF CONTENTS

1.0	INTRODUCTION.....	1-1
2.0	GEOLOGY/HYDROGEOLOGY	2-1
3.0	DATA ACQUISITION AND LOGISTICS	3-1
4.0	DATA PROCESSING.....	4-1
5.0	INTERPRETATION AND RESULTS.....	5-1
5.1	TDEM SOUNDING DATA.....	5-1
5.2	GEOELECTRIC CROSS-SECTION – LINE 1 (A-A').....	5-1
5.3	GEOELECTRIC CROSS-SECTION – LINE 2 (B-B')	5-2
5.4	GEOELECTRIC CROSS-SECTION – LINE 3 (C-C')	5-2
5.5	HYDROGEOLOGIC INTERPRETATIONS	5-3
6.0	CONCLUSIONS AND RECOMMENDATIONS.....	6-1
7.0	CERTIFICATION AND DISCLAIMER.....	7-1

LIST OF FIGURES AT THE END OF THE TEXT

Figure 1-1: TDEM Loop Location Map
Figure 2-1: Schematic Hydrogeologic Cross-Section
Figure 2-2: Illustration of Ghyben-Herzberg Principle
Figure 2-3: Characteristic Resistivity Ranges
Figure 2-4: Geologic and Topographic Map
Figure 3-1: Schematic Layout of TDEM System
Figure 4-1: Sounding L-1 Example Inversion Output Apparent Resistivity Curve
Figure 4-2: Sounding L-1 Example of Tabulated Data from Inversion
Figure 5-1: Geoelectric Cross-Section – Line 1 (A-A')
Figure 5-2: Geoelectric Cross-Section – Line 2 (B-B')
Figure 5-3: Geoelectric Cross-Section – Line 3 (C-C')
Figure 5-4: Summary Interpretation Map

LIST OF TABLES

Table 3-1: Daily Log of Field Activities

APPENDICES

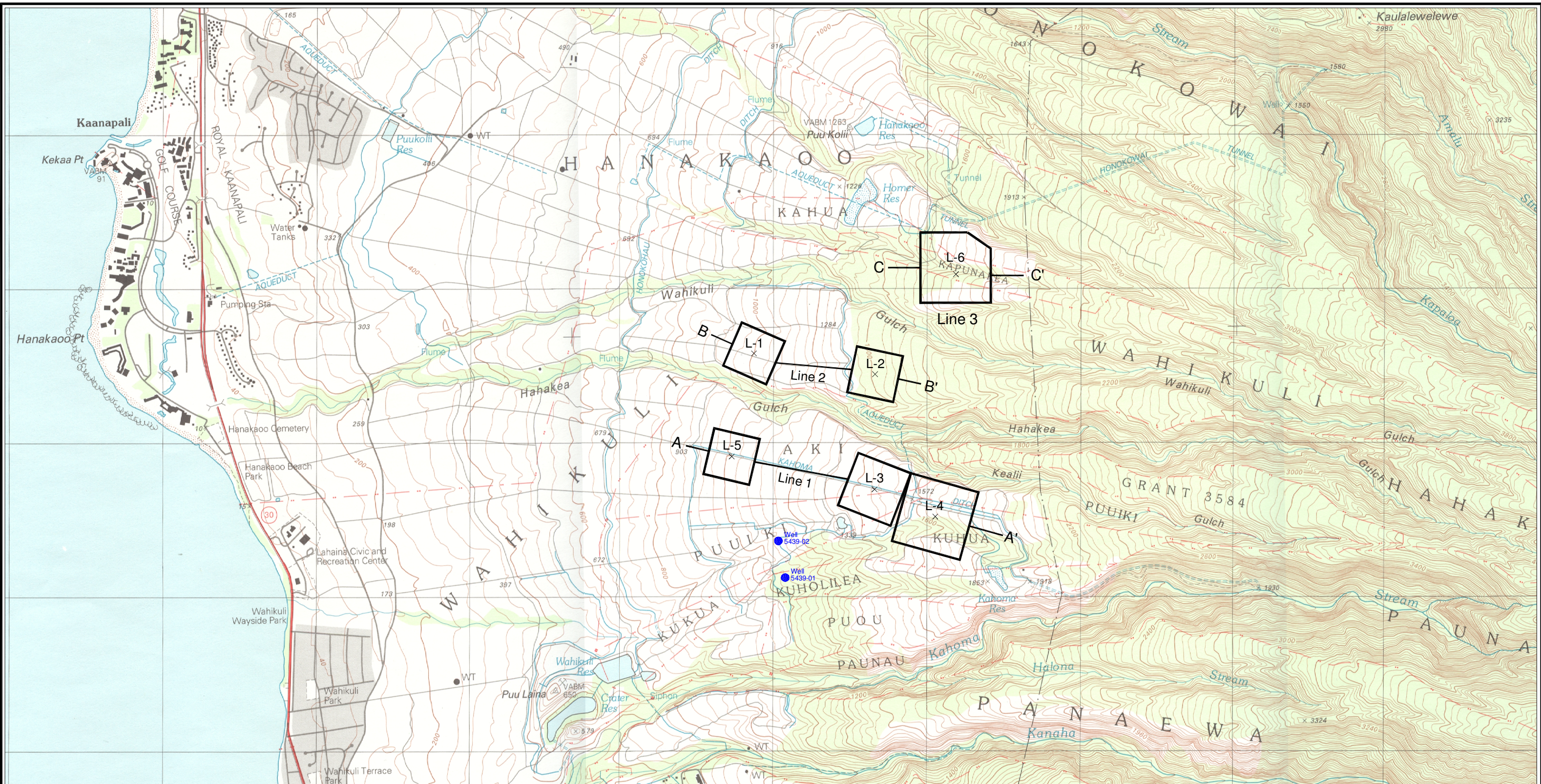
Appendix A: Technical Note
Appendix B: Sounding Curves and Data Printouts, GPS Coordinates of TDEM Soundings and
Evaluation of the Pump Test Results of Wahikuli Wells 1 and 2.
Appendix C: CD with files (.PDF) of Report and Figures

1.0 INTRODUCTION

This report contains the procedures and results of surface Time Domain Electromagnetic (TDEM) geophysical surveys performed for groundwater resource evaluation on property located in the Lahaina District, above the town of Kaanapali, Maui. The property included land owned by West Maui Land Company, Inc (WMLCI) and Kaanapali Land Management Corporation (KLMC). Zapata Incorporated, Blackhawk Division (ZAPATA/Blackhawk) performed the surveys for Belt Collins Hawaii Ltd (BCHL) and Tom Nance Water Resource Engineering (TNWRE) from October 20 through October 26, 2009. The project is known as Villages of Leiali'i and was accomplished for the Hawaii Housing Finance and Development Corporation (HHFDC) located in Honolulu, Hawaii.

The main objective of the TDEM surveys was to explore for basal and high-level groundwater occurrences on the property. The surveys were conducted at six TDEM sites to help determine the location for a future groundwater well. Figure 1-1 shows the locations of the TDEM soundings taken during this survey.

TDEM is a geophysical method that determines from the surface the geoelectric section (resistivity layering) of the subsurface. From the geoelectric section, information about geology and water quality can be inferred. This is possible because the electrical resistivity of the earth depends on lithology, porosity, the degree of saturation, and concentration of dissolved solids in the groundwater. Geophysical surveys, combined with other hydrogeologic information, are used to provide optimum locations for water well placement and well completion depths.

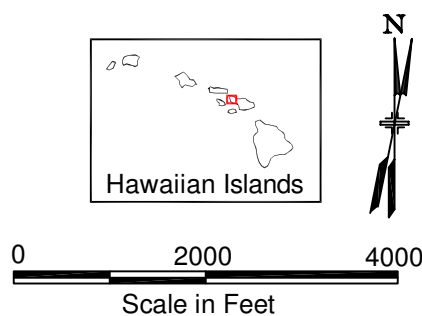


Explanation

1 X TDEM Sounding

A-A' Section Line

Well 5439-02



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Kaanapali, Maui

Project No:
5156

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Nov., 2009

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HJV

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RJB

Scale:
1"=2000'

Figure:
1-1

Geophysical TDEM Survey
Location Map
Lahaina District
Island of Maui

2.0 GEOLOGY/HYDROGEOLOGY

Groundwater resources occur on the Hawaiian Islands basically in two modes:

- In a basal mode where a lens of fresh water floats on seawater, and
- In a high-level mode where the fresh groundwater occurrence is controlled by damming structures (i.e. intrusives, dikes, etc).

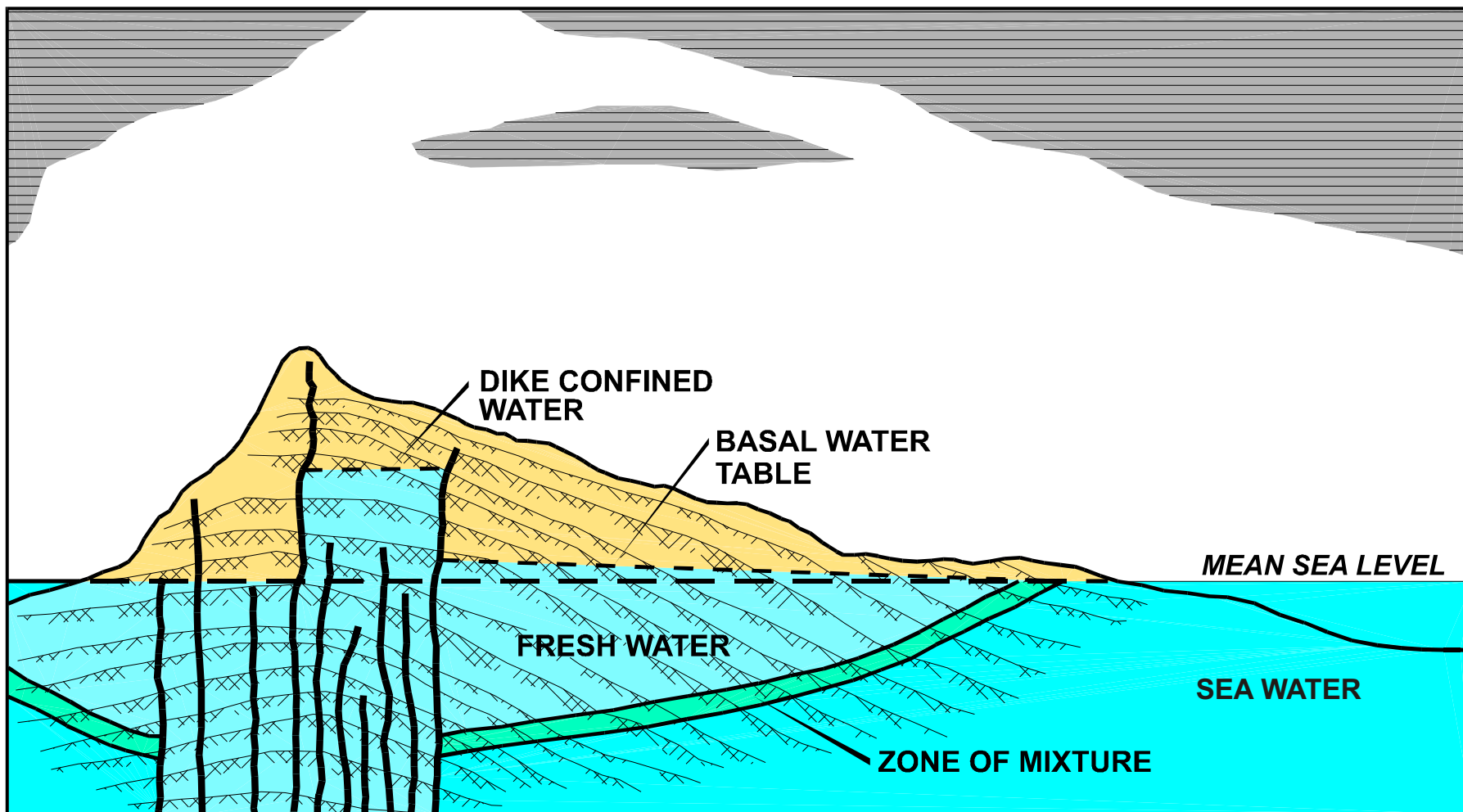
Figure 2-1 illustrates the basic geologic and hydrologic framework of the Island of Maui and the two modes of groundwater occurrences. Fresh groundwater may also occur in areas between these two modes, but production is expected to be highly variable. TDEM soundings previously taken on Hawaii have reliably mapped basal mode groundwater and the boundary between fresh water in the basal mode and high-level water occurrences.

Basal mode groundwater is resting approximately at sea level near the ocean surrounding the Island of Maui. This is generally due to the fact that the volcanic rocks, which comprise the island, allow rainfall to percolate with little impedence directly downward through the rock mass (reference Figure 2-1). The fresh water floats directly on seawater encroaching from the ocean. Fresh water flows laterally toward the ocean causing the fresh water lens to be thinner near the shoreline. When groundwater is under static equilibrium conditions, the Ghyben-Herzberg Principle states that for every one foot of fresh water above sea level approximately 40 feet of fresh water will exist below sea level (shown in Figure 2-2). The change from fresh water to seawater (transition zone) at depth may be relatively sharp (i.e. occurring over several tens of feet) or more gradual, depending upon hydrologic flux, horizontal and vertical permeability contrast, and other geologic factors (such as dikes, etc). It is assumed, when resolving TDEM sounding data, that seawater saturated volcanics occur at the midpoint of the transition zone.

TDEM surveys are utilized to map the resistivity stratification of the subsurface. From numerous TDEM surveys on Maui and calibration of TDEM data at groundwater wells, characteristic ranges of subsurface resistivities have been derived for the geologic/hydrologic units shown in Figure 2-3. Some overlap in resistivity values occurs between the units; however, other factors (such as elevation) can be used to help separate the units. Therefore, the main geologic/hydrologic units that can be derived from TDEM surveys include:

- Depth to seawater saturated volcanic rocks. This occurs in basal mode situations, and by using the Ghyben-Herzberg principle, the thickness of the basal fresh water lens can be calculated.
- Weathered volcanic layers (laterite). These lower resistivity units are generally relatively thin layers (100 ft to 200 ft thick) that normally occur at or near the ground surface.
- Clay-poor and fresh water saturated volcanic rocks. These formations generally exhibit high resistivity values. The extent of fresh water saturation is normally based on geographic and elevation information, and it should be noted that fresh water layers cannot be directly detected in the TDEM data.

Groundwater damming structures (i.e. intrusives, dikes) are inferred with TDEM data by uncharacteristic sounding curves (distorted by 2-D structures), and by soundings that change between detection of seawater at depth (indicating basal mode groundwater) and soundings that map high resistivities to depths below sea level (indicating high-level groundwater). Figure 2-4 illustrates the geologic and topographic map of the West Maui Volcano showing lava flows, cinder cones, fissure vents and faults in the project area. Also shown on the map are the locations of the TDEM soundings taken during this survey.



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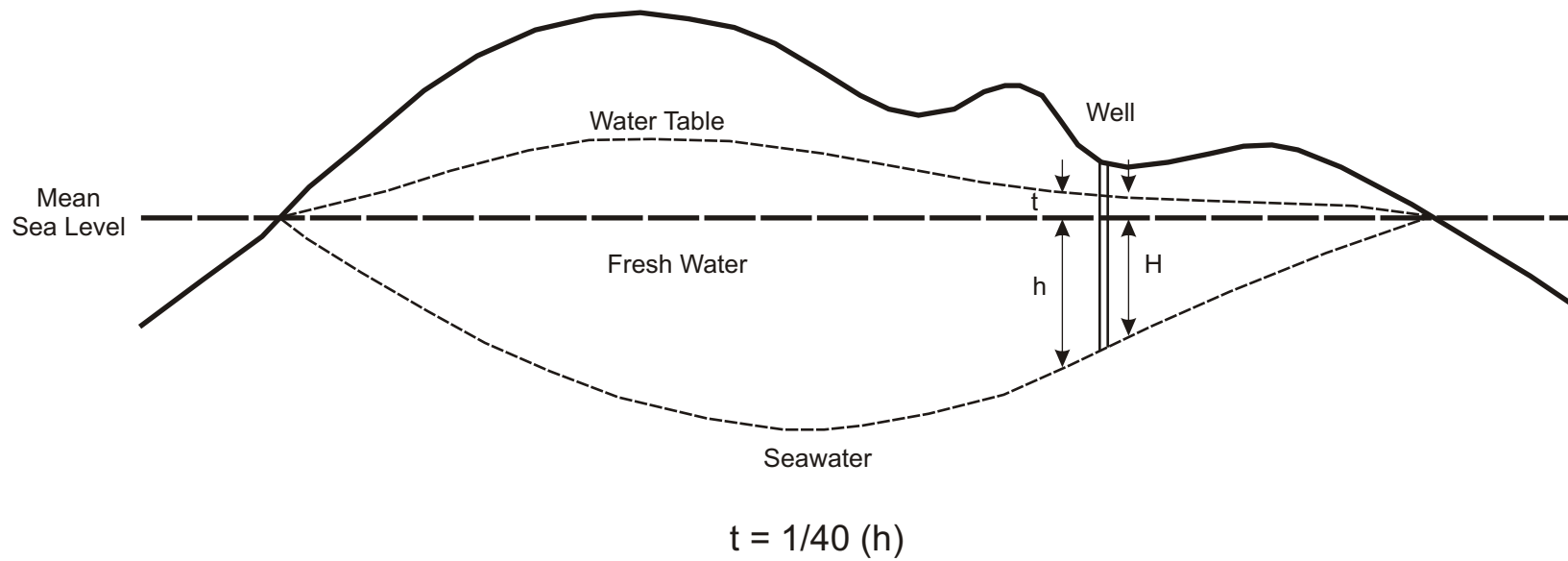
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HJV

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Figure:
2-1

Schematic Hydrogeologic
Cross Section
Island of Maui



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Figure:
2-2

Illustration of the
Ghyben-Herzberg Principle

**Dry Unweathered or Fresh-Brackish
Water Saturated Volcanics**

**Ash Flows, Weathered
Volcanics or Intrusives**

**Seawater
Saturated Volcanics**

1 10 100 1000

Resistivity (Ohm-m)



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**Characteristic
Resistivity Ranges**
Island of Maui

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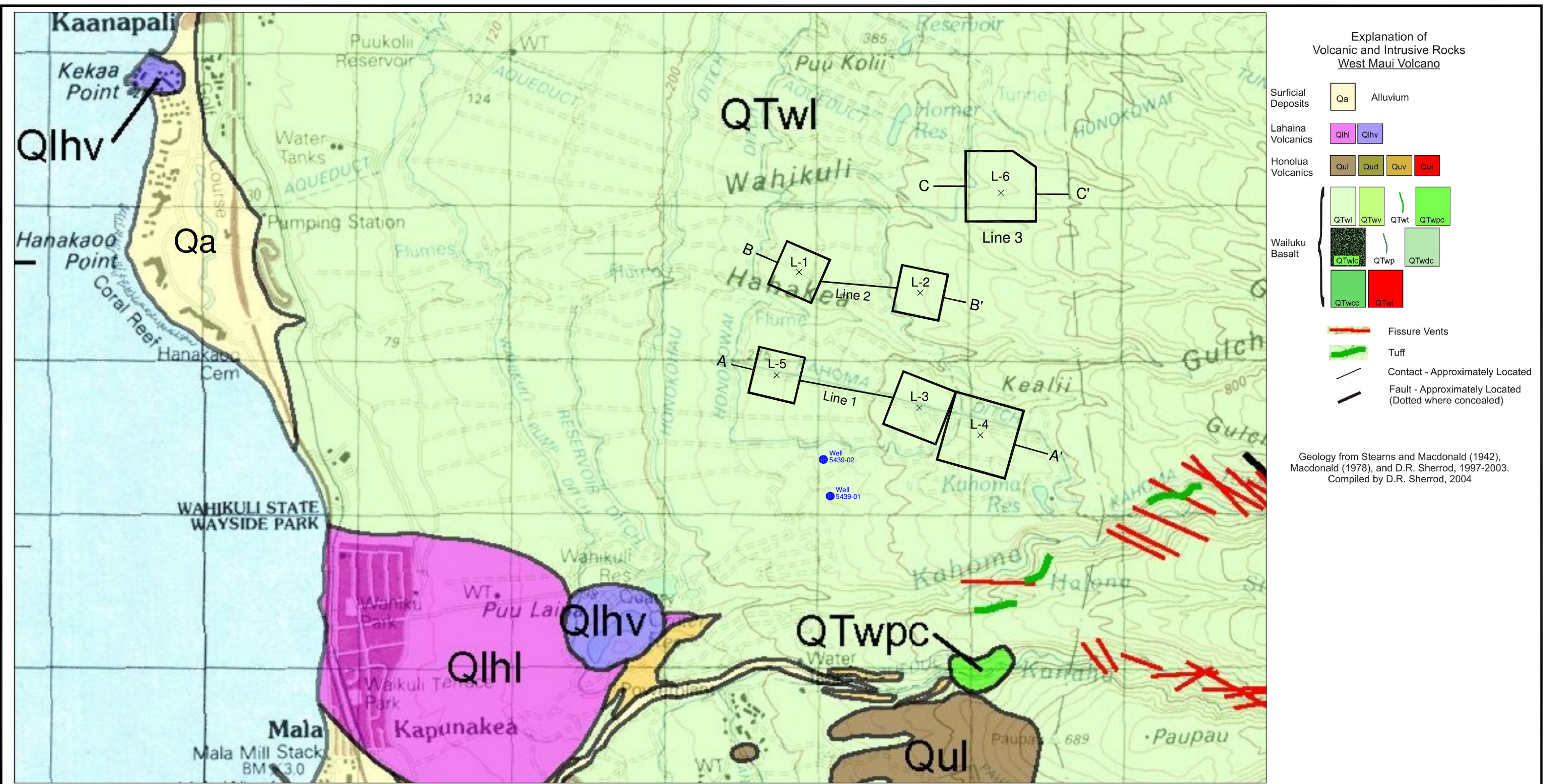
RJB

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Figure:

2-3



Explanation of Volcanic and Intrusive Rocks West Maui Volcano

Surficial Deposits: Qa Alluvium

Lahaina Volcanics: Qlhl, Qlhv

Honolua Volcanics: Qul, Qud, Quv, Qui

Wailuku Basalt: QTwl, QTww, QTwt, QTwpc, QTwlc, QTwp, QTwdc, QTwcc, QTwi

Fissure Vents: Red line with cross-ticks

Tuff: Green line with cross-ticks

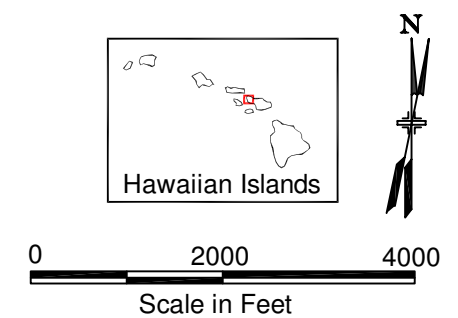
Contact - Approximately Located: Thin black line

Fault - Approximately Located (Dotted where concealed): Thick black line

Geology from Stearns and Macdonald (1942), Macdonald (1978), and D.R. Sherrod, 1997-2003. Compiled by D.R. Sherrod, 2004

Explanation

- TDEM Sounding
- Section Line
- Well 5439-02
- Contour Interval 40 meters



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5156	Nov., 2009	HJV	RJB	1"=2000'	2-4

Geologic & Topographic Map
West Maui Volcano
Lahaina District
Island of Maui

3.0 DATA ACQUISITION AND LOGISTICS

ZAPATA/Blackhawk mobilized a field crew consisting of a project geophysicist and geophysical technician to perform the geophysical surveys on land owned by WMLCI and KLMC located above the town of Kaanapali, Maui. The ZAPATA/Blackhawk field crew and TDEM equipment were mobilized from Golden, Colorado to Kahului, Maui. Prior to conducting the surveys, ZAPATA/Blackhawk personnel coordinated with TNWRE and WMLCI personnel to determine property access and get keys for gate locks. During the course of field work, the ZAPATA/Blackhawk crew coordinated nightly with TNWRE for project direction and oversight. A daily log of field activities during the TDEM surveys is presented in Table 3-1.

The Geonics EM37 geophysical system was utilized for the TDEM surveys. The EM37 system contains both a portable motor-generator powered transmitter and a PROTEM digital receiver. The main purpose of the TDEM measurements is to derive both the vertical and lateral variations in the geoelectric section (resistivity) of the subsurface. To accomplish this, TDEM soundings were collected using a central-loop array at each site. The square transmitter wire-loops were constructed using 12-gauge insulated copper wire laid on the ground surface, as illustrated in Figure 3-1. The dimensions of the transmitter wire-loops ranged from 1,000 ft by 1,000 ft to 1,500 ft by 1,500 ft. The motor-generator and transmitter were placed in each transmitter loop and square-wave current pulses were driven through the wire-loop using a current ranging from 10 to 14 amperes. The current pulses induce eddy current flow in the subsurface of the ground. A solid-core receiver coil (1-meter diameter) attached to the PROTEM receiver was positioned in the center of each wire-loop and was used to record the decay of the secondary magnetic field from the eddy currents induced in the subsurface. The effective exploration depth of a 1,000 ft by 1,000 ft transmitter wire-loop array has been determined to be approximately 2,500 ft below ground surface. Therefore, at ground surface elevation of 1,000 ft, a search depth of approximately 1,500 ft below sea level is obtained. Greater exploration depths are reached with larger transmitter wire-loops and there are several factors that affect the depth of investigation; these include ground resistivity (in ohm-m) and surrounding ambient cultural interference (i.e. 60-cycle powerline, pipelines, etc). A technical note describing the principles of TDEM with case histories is given in Appendix A.

The TDEM data acquired at each sounding site consisted of measurements utilizing several receiver gain settings and two transmitter frequencies in order to obtain data over the longest possible time interval and ensure data quality. The data were recorded using base frequencies of 3 Hz and 30 Hz to obtain the maximum search depth for each TDEM sounding. For data quality control (QC) purposes, additional data were collected at a minimum of two designated locations (200 ft offset in each direction) from the center, for comparison to the central-loop data. The data from each sounding were recorded in solid-state memory in the PROTEM receiver and transferred nightly to a PC for processing. All of the TDEM sounding data collected at the project site were of excellent quality with no distortions due to local cultural interferences (i.e. metal fences, pipelines or powerlines).

The corners of the transmitter wire-loops were registered to existing road junctions and irrigation ditches located on the property. In several cases, landmarks such as fences and gates were also used to position the wire-loops on the topographic map along with a distance measuring device (hip-chain) and compass. In addition, a hand-held global positioning system (GPS) with differential capability was utilized to map the center and transmitter location of each sounding. The GPS coordinates were used to position each loop center on a geo-referenced topographic map and the center elevation was subsequently derived from that position. Due to extreme road conditions (wash-outs and boulders), rental of a Polaris 4X4 ATV was required to transport the TDEM equipment (generator, wire spools, etc) into Soundings L-1 and L-2. As a result of poor road access and overgrown fields (8-10 ft tall Guinea grass and Lantana brush), a total of six TDEM soundings were measured during seven days of fieldwork. The GPS coordinates and elevations of the TDEM loop centers and corners along with several road intersections are given in Table 3-2 in Appendix B.

Table 3-1 Daily Log of Field Activities Villages of Leiali'i, Kaanapali, Maui - TDEM Survey	
Date (2009)	Activity
October 12	Ship TDEM geophysical equipment from Golden, CO to Kahului, Maui.
October 19	Mobilize ZAPATA/Blackhawk personnel from Golden, CO to Kahului, Maui.
October 20	Unpack TDEM equipment at hotel and organize into SUV. Meet with WMLCI field personnel, perform recon of access roads to Loops L-3 and L-4, receive key for gate lock. Begin TDEM survey, lay out 2 wires on Sounding L-3. Test motor-generator with EM37 transmitter and PROTEM. Discuss survey with TNWRE.
October 21	Complete layout of wire-loop and collect data on Sounding L-3. Pick up wire-loop, move to Sounding L-4 and lay out 2 wires. Download data to PC and perform preliminary data analysis at hotel. Discuss results with TNWRE.
October 22	Finish layout of wire-loop and acquire data on Sounding L-4. Pick up wire-loop. Contact KLMC field personnel to discuss access to Soundings L-1, L-2 & L-6. Perform recon of access road to Soundings L-1 and L-2. Due to poor road conditions (wash-outs, boulders), decision is made to rent Polaris 4X4 ATV to transport TDEM equipment into sites. Download data to PC and perform preliminary data analysis at hotel. Discuss results with TNWRE.
October 23	Rent Polaris 4X4 ATV from Service Rentals in Lahaina. Begin shuttling TDEM equipment from SUV to Sounding L-1. Lay out wire-loop and acquire data on Sounding L-1. Pick up wire-loop and begin laying out 2 wires on Sounding L-2. Download data to PC and perform preliminary data analysis at hotel. Discuss results with TNWRE.
October 24	Finish laying out wire-loop and data collection on Sounding L-2. Pick up wire-loop and shuttle out equipment to SUV. Download data to PC and perform preliminary data analysis at hotel. Discuss results with TNWRE.

*Time Domain Electromagnetic Surveys for Assisting in Determining the
Groundwater Resources on Property Located in the Lahaina District
Above Kaanapali, Island of Maui
Data Acquisition and Logistics*

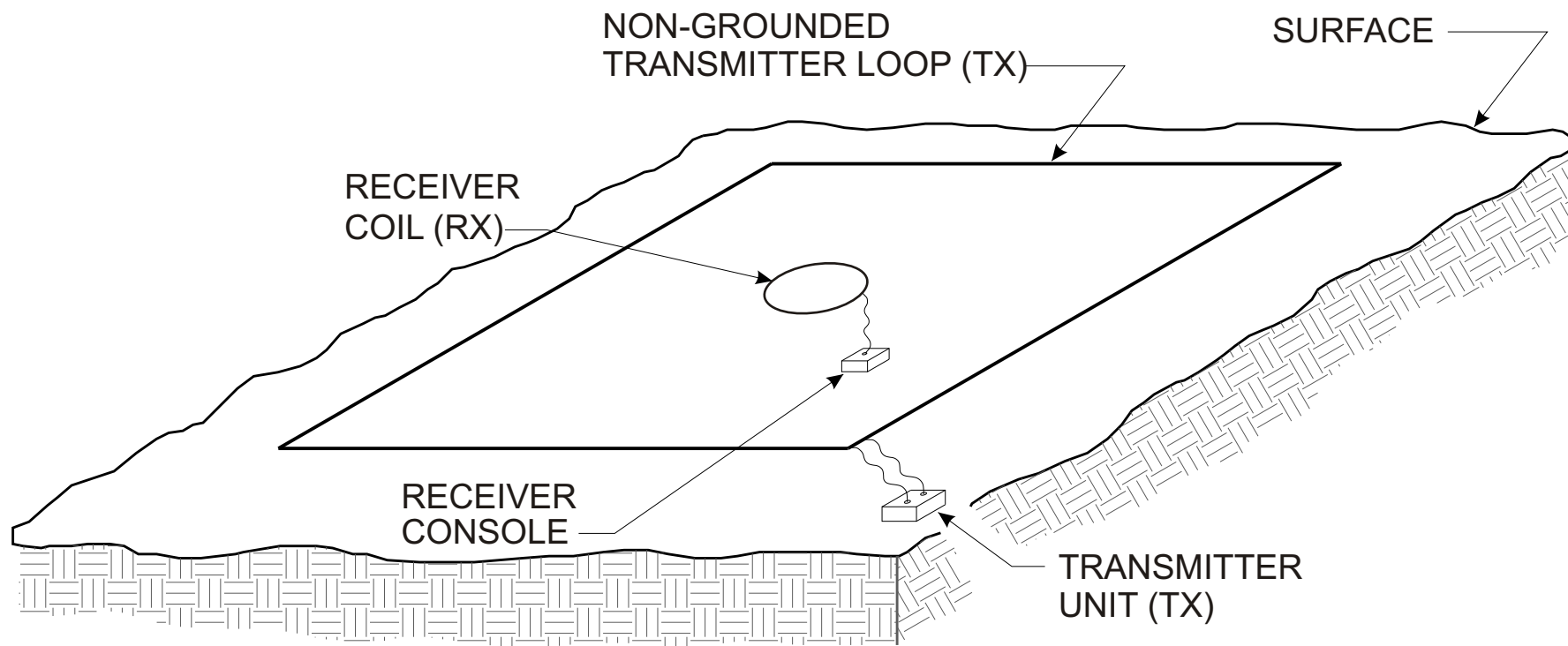
October 25	Recon access roads for Sounding L-6. Lay out wire-loop and acquire data on Sounding L-6. Pick up wire-loop. Download data to PC and perform preliminary data analysis in hotel. Discuss results with TNWRE. Decision is made by TNWRE to place Sounding L-5 along Kahoma Irrigation Ditch road making Sounding L-3.
October 26	Return Polaris 4X4 ATV to Service Rentals. Lay out wire-loop and collect data on Sounding L-5. Pick up wire-loop. Download data to PC and perform preliminary data analysis in hotel. Discuss results with TNWRE. Decision is made by TNWRE that TDEM survey is finished.
October 27	Pack up TDEM equipment into shipping boxes and deliver to FedEx office in Kahului, Maui.
October 28-29	Demobilize Blackhawk personnel from Kahului, Maui to Golden, CO.

Table 3-2

GPS Coordinates for TDEM Soundings (NAD 83 Decimal Degrees and UTM in meters)

Belt Collins Hawaii Ltd, Villages of Leialii, Kaanapali, Maui

ID	Location	Northing	Westing	Elev (ft)	Elev (m)	UTM (N)(m)	UTM (E)(m)	Comments
1	Center Loop 3	20.90752708	156.6474176	1440	439	2313707	744703	Center of Transmitter Loop 3, Near Kahoma Ditch Road
2	NE Corner Loop 3	20.90838279	156.6455516	1560	475	2313805	744896	NE Corner of Loop 3, On Dirt Road & Irrigation Ditch
3	Center Loop 4	20.90600325	156.6440283	1660	506	2313543	745058	Center of Transmitter Loop 4, S of Kahoma Ditch Road
4	NW Corner Loop 4	20.90838279	156.6455516	1560	475	2313805	744896	NW Corner of Loop 4, On Dirt Road & Irrigation Ditch
5	SW Corner Loop 1	20.91496417	156.6574499	920	280	2314515	743647	SE Corner Loop 1, On Dirt Road
7	Center Loop 1	20.91558385	156.6555692	1000	305	2314587	743842	Center of Transmitter Loop 1
10	SW Corner Loop 2	20.91318998	156.6494419	1300	396	2314331	744483	SW Corner of Loop 2, On Dirt Road & Irrigation Ditch
12	Center Loop 2	20.91417938	156.6477798	1410	430	2314443	744654	Center of Transmitter Loop 2
13	SW Corner Loop 7	20.91838441	156.6447838	1540	469	2314913	744959	SW Corner of Loop 7, On Dirt Road & Irrigation Ditch
15	Center Loop 7	20.92002735	156.6425477	1660	506	2315099	745189	Center of Transmitter Loop 7
18	Side Center on Road	20.90910648	156.6552422	1100	335	2313870	743886	Side Center of Loop on Dirt Road
19	Center Loop 5	20.90929231	156.6567882	1010	308	2313888	743725	Center of Transmitter Loop 5, On Kahoma Ditch Road
20	Side Center on Road	20.90984291	156.6581962	940	286	2313947	743578	Side Center of Loop on Dirt Road
21	Kahoma & Aaron's Rd	20.90674563	156.6455983	1560	475	2313623	744893	Jct of Kahoma Ditch Road & Aaron's Road
22	Kahoma & Irrig Ditch	20.90596997	156.6417124	1800	549	2313543	745299	Jct of Kahoma Ditch Road & Lower Irrigation Ditch



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Schematic layout of TDEM system
with locations of TX and RX
for Central Loop Array
measurements

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Scale:

No Scale

Figure:

3-1

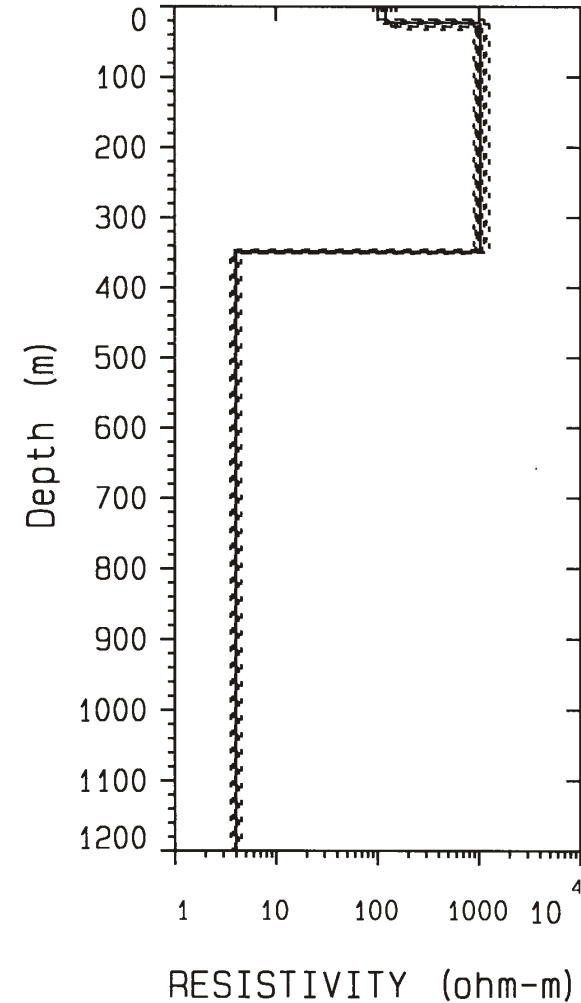
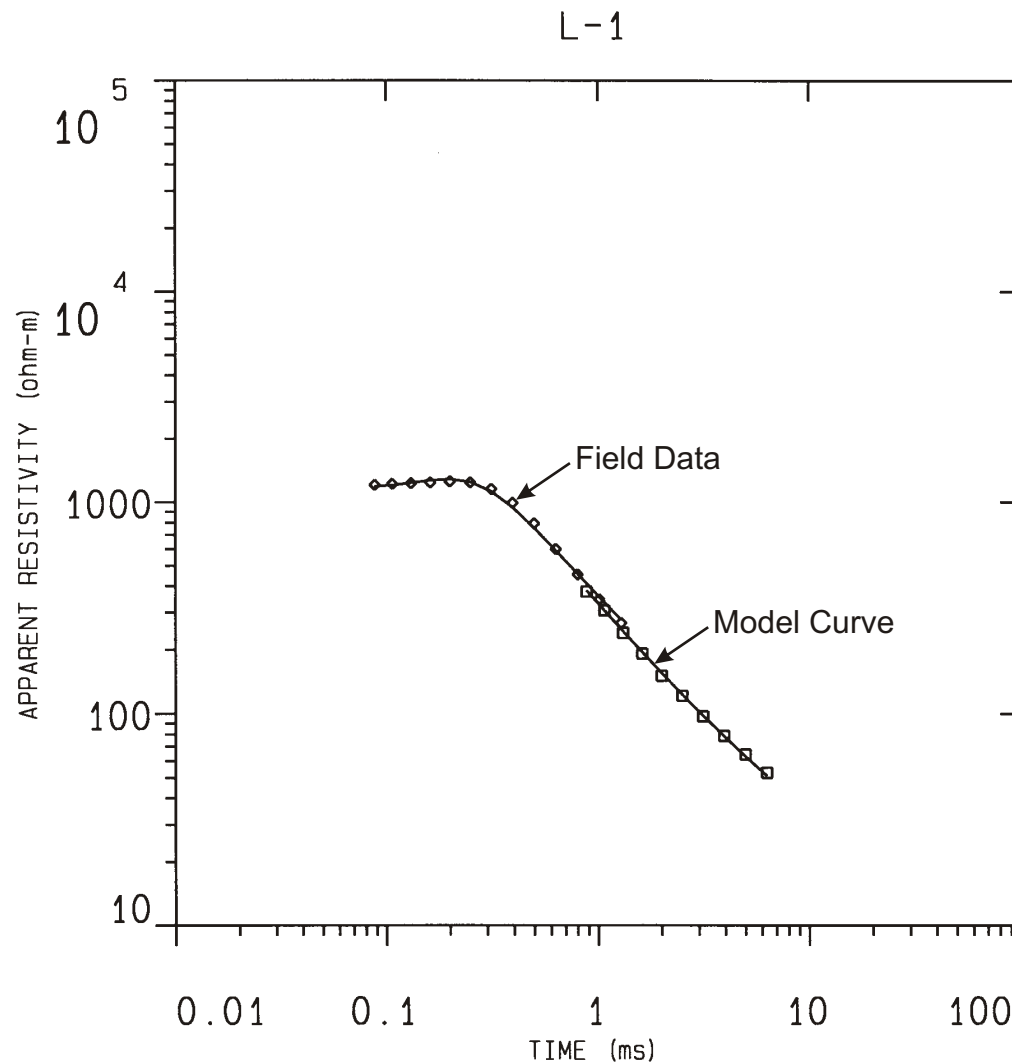
4.0 DATA PROCESSING

The geophysical field data collected for each TDEM sounding was transferred from the Geonics PROTEM digital receiver to a PC for editing and processing. Processing of the TDEM data starts with averaging of the electromotive forces recorded for positive and negative receiver polarities. Next, the measurements collected at two base frequencies (3 and 30 Hz) and amplifier gains are combined to give one voltage decay curve (transient). The electromotive forces collected from 20 logarithmical spaced time-channels (gates) of the decay curve are subsequently entered into the TEMIXXL (Interpex Ltd) inversion program. The data are used to obtain a one-dimensional (1-D) geoelectric section that best matches the observed (field data) decay curve.

The TEMIXXL inversion program requires an initial model of the geoelectric section measured. The initial model includes the number of layers, resistivities and thickness for each of the layers. This model is usually derived from knowledge of the geologic section or from data obtained from drill holes or electric logs. The inversion program is then allowed to adjust the layer thickness and the resistivities, so that the model curve converges to best fit the field data. The inversion program does not change the total number of layers within the model curve, but allows all other parameters to change freely or they can optionally be fixed constant. To determine the influence of the number of layers on the solution, separate inversions with a different number of layers are run. Subsequently, the model with the least number of layers that best fits the field data is used.

An example of the output of the inversion program is shown on Figure 4-1 for Sounding L-1. This figure shows the measured data points (in terms of apparent resistivity) superimposed on a solid line on the left panel. The solid line represents the computed forward model for the geoelectric section on the right panel. This geoelectric section is the best match obtained by the inversion program. Figure 4-2 shows the tabulated inversion parameters consisting of measured data, computed data for best match solutions and an example of the table of inversion statistics. A three-layer inversion model is shown for Sounding L-1. The model displays a thin (75 ft) resistive (120 ohm-m) upper layer overlying a resistive (1024 ohm-m) second layer. The third layer exhibits a very low resistivity (4.0 ohm-m) and the depth to the top of the third layer is modeled at -144 ft below sea level in the section. The third layer is interpreted as conductive seawater.

The interpreted geoelectric section derived from each TDEM sounding is not unique. The magnitude of each individual layer resistivity and thickness can normally be varied within a limited range with no significant change to the fit of the geoelectric model of the data. This variation is termed equivalence. An equivalence analysis was performed for each TDEM sounding. Both Figures 4-1 and 4-2 also show the equivalence analysis for Sounding L-1. This sounding is typical of the TDEM data which shows a +/-5% equivalence in depth determinations and +/-10% in individual layer resistivities. The inversion results for each sounding are given in Appendix B.



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Scale:

No Scale

Figure:

4-1

Sounding L-1
Example Inversion Output
Apparent Resistivity Curve
Lahaina District
Island of Maui

DATA SET: L-1

CLIENT: Belt Collins Hawaii, Ltd
 LOCATION: Kaanapali, Maui
 COUNTY: Maui
 PROJECT: Villages of Lei'Alii
 LOOP SIZE: 305.000 m by 305.000 m
 COIL LOC: 0.000 m (X), 0.000 m (Y)
 SOUNDING COORDINATES: E: 1.0000 N: 2.0000
 DATE: 10-23-09
 SOUNDING: 1
 ELEVATION: 305.00 m
 EQUIPMENT: Geonics PROTEM
 AZIMUTH:
 TIME CONSTANT: NONE
 SLOPE: NONE

Central Loop Configuration
 Geonics PROTEM System

FITTING ERROR: 3.488 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	CONDUCTANCE (Siemens)
1	119.5	23.00	305.0	1000.0
2	1024.3	325.5	281.9	925.0
3	4.01		-43.52	-144.0

ALL PARAMETERS ARE FREE

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER	MINIMUM	BEST	MAXIMUM
RHO			
1	90.963	119.581	152.842
2	882.156	1024.397	1258.035
3	3.559	4.018	4.529
THICK			
1	18.007	23.003	32.409
2	317.125	325.518	331.569
DEPTH			
1	18.007	23.003	32.409
2	345.654	348.520	351.136

Equivalence
 Analysis

CURRENT: 13.50 AMPS EM-58 COIL AREA: 100.00 sq m.
 FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 150.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.881	118.5	116.2	1.95
2	1.06	99.31	99.22	0.0846
3	1.31	85.79	83.50	2.66
4	1.61	71.17	69.60	2.21
5	2.00	59.70	57.38	3.89
6	2.50	47.45	46.52	1.95
7	3.14	37.50	37.17	0.878
8	3.95	28.99	29.26	-0.960
9	4.99	22.04	22.66	-2.79
10	6.31	16.41	17.25	-5.12

CURRENT: 13.50 AMPS EM-58 COIL AREA: 100.00 sq m.
 FREQUENCY: 30.00 Hz GAIN: 3 RAMP TIME: 150.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
11	0.0881	6536.1	6672.3	-2.08
12	0.106	3961.3	4055.3	-2.37
13	0.131	2347.7	2331.9	0.671
14	0.161	1373.7	1325.0	3.54
15	0.200	789.5	759.4	3.81
16	0.250	460.2	457.1	0.674
17	0.314	290.5	302.4	-4.08
18	0.395	205.5	221.1	-7.57
19	0.499	161.2	172.7	-7.10
20	0.631	135.9	139.2	-2.42
21	0.799	114.3	113.0	1.17
22	1.01	94.62	91.27	3.53
23	1.28	76.75	73.03	4.85

PARAMETER RESOLUTION MATRIX:

"F" INDICATES FIXED PARAMETER

P 1 0.54
 P 2 0.15 0.29
 P 3 0.04 -0.11 0.72
 T 1 -0.41 -0.24 0.02 0.39
 T 2 0.03 0.02 -0.02 0.05 0.99
 P 1 P 2 P 3 T 1 T 2



Belt Collins Hawaii LTD
 Villages of Lei'ali'i
 Kaanapali, Maui

Sounding L-1
 Example of Tabulated Data
 From Inversion
 Lahaina District
 Island of Maui

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Date:
 November, 2009

Drawn By:
 HJV

Checked By:
 RJB

Scale:
 No Scale

Figure:
 4-2

5.0 INTERPRETATION AND RESULTS

5.1 TDEM SOUNDING DATA

From each TDEM sounding, the geoelectric section of the subsurface is derived. The results of the one-dimensional (1-D) inversion of the individual TDEM soundings can be linked together (layers with similar resistivities) to create a 2-D geoelectric cross-section along a survey line. A total of six TDEM soundings were collected along dirt roads on both the WMLCI and KLMC property during this project (reference Figure 1-1). From the TDEM surveys three separate geoelectric cross-sections were generated. The correlation between the geoelectric layers and lithologic units (illustrated on Figure 2-3) were used to interpret the geoelectric cross-sections.

5.2 GEOELECTRIC CROSS-SECTION – LINE 1 (A-A')

Figure 5-1 shows the layered geoelectric cross-section interpreted from TDEM data collected along Line 1. The TDEM soundings were located along the Kahoma Irrigation Ditch road located south of the Hahakea Gulch in a roughly west to east direction. The center of Sounding L-5 was located in an abandoned sugar cane field at 1,010 ft elevation level while Sounding L-3 was positioned at an elevation of 1,440 ft along the dirt road. The center of Sounding L-4 was situated above Sounding L-3 at the 1,660 ft elevation level and was located about 200 ft south of the Kahoma Ditch road.

A three-layer cross-section is interpreted for each sounding along Line 1. The upper two layers in the geoelectric cross-section, beneath all soundings, exhibit intermediate to high resistivities that range from 132 ohm-m to > 1,000 ohm-m. The layers are interpreted as dry, clay poor volcanic formations located both above and below sea level. The thickness of the top layer is interpreted to range from about 65 ft to 118 ft across the site. Where the second layer occurs below sea level (>1,000 ohm-m), it is expected to be saturated with fresh-brackish basal mode groundwater. The third layer in the section, beneath Sounding L-5, shows intermediate resistivity (20 ohm-m) occurring at a depth of 206 ft below sea level (bsl) and is interpreted to represent weathered volcanic layers at depth beneath this sounding. This lower layer resistivity may be the result of 1.) Distortion of the data by 2-D geologic structures (i.e. intrusives, dikes); 2.) The presence of significant amounts of fine-grained materials (clays) in this area of the section; or 3.) Saturation of this portion of the section with brackish groundwater. Information was obtained regarding a water well in the area (State Well No. 5439-02, Wahikuli Well 2), which is located approximately 2,000 ft southeast of Sounding L-5 (elevation 1,100 ft), and is reported to contain basal groundwater with static water level (head) of 5.0 ft (per com T. Nance). Because Sounding L-5 did not detect conductive seawater at depth, a direct comparison of head (using the Ghyben-Herzberg Principle) with this water well cannot be made at this location. However, information from pumping of Well 2 shows a time-dependent component of drawdown and recovery which indicates water being drawn from a compartment with a boundary effect that is likely caused by an unknown subsurface feature in this well. Therefore, a subsurface geologic feature is likely causing non-layered earth conditions (i.e. 2-D high angle fault or dike) that may act as a possible groundwater damming structure beneath this area of the

property. There are, however, no surface geologic features (i.e. cinder cones, etc.) mapped in the immediate vicinity of Sounding L-5.

The results for Soundings L-3 and L-4 show high resistivity ($>1,000$ ohm-m) layers both above and below sea level to depth of about 955 ft bsl for Sounding L-3 and 1,860 ft bsl for Sounding L-4. Therefore, these results would place an interpreted groundwater barrier (i.e. lateral discontinuity) midway between Soundings L-5 and L-3 as shown on the cross-section. The lower layers of Soundings L-3 and L-4 show high resistivity (110 ohm-m) at depth (1,000 ft bsl) and these soundings are interpreted to be located above a groundwater damming structure (i.e. intrusives) in the section. Therefore, the potential for high-level groundwater may exist beneath these locations.

5.3 GEOELECTRIC CROSS-SECTION – LINE 2 (B-B')

The layered geoelectric cross-section from the TDEM data taken along Line 2 is shown in Figure 5-2. These soundings were located along a dirt road between the Hahakea and Wahunukuli Gulches in a west to east direction. The center of Sounding L-1 was situated in an abandoned sugar cane field at the 1,000 ft elevation level while the center of Sounding L-2 was positioned east of Sounding L-1 above the irrigation ditch at 1,410 ft elevation.

A three-layer cross-section is interpreted for each sounding along Line 2. The upper layer in the geoelectric section exhibits resistivities that range from 120 to 247 ohm-m and is interpreted as dry clay poor volcanic layers across the site. The thickness of the top layer is interpreted to range from about 75 ft to 117 ft along the line. The second layer in the section shows high resistivity ($>1,000$ ohm-m), that is interpreted to represent dry clay poor volcanic layers above sea level and where the layer occurs below sea level it is expected to be saturated with fresh-brackish basal mode groundwater. The third layer in the section beneath Sounding L-1 shows low resistivity (4.0 ohm-m) and is interpreted to represent seawater saturated volcanic layers beneath this sounding. The calculated thickness of the fresh-brackish basal groundwater lens is 144 ft (head of 3.6 ft) beneath Sounding L-1.

The results for Sounding L-2 show high resistivity ($>1,000$ ohm-m) layers that occur both above and below sea level to depth of about 1,053 ft bsl. From the TDEM data, a groundwater barrier is interpreted midway between Soundings L-1 and L-2. Sounding L-2 is expected to be located above the groundwater damming structure (i.e. intrusives) in the section and the potential for high-level groundwater may exist beneath this sounding.

5.4 GEOELECTRIC CROSS-SECTION – LINE 3 (C-C')

Figure 5-3 shows the layered geoelectric cross-section interpreted from TDEM data collected along Line 3. The center of Sounding L-6 was located at the 1,660-ft elevation level above the Horner Reservoir on the north side of Wahunukuli Gulch.

A three-layer section is interpreted for Sounding L-6. The upper two layers in the geoelectric section exhibit high resistivities that range from 245 ohm-m to $> 1,000$ ohm-m. These layers are interpreted as dry, clay poor volcanic formations located both above and below sea level. Where

the second layer occurs below sea level it is expected to be saturated with fresh-brackish basal mode groundwater. The third layer in the section shows high resistivity (137ohm-m) occurring at a depth of 1,434 ft bsl and is interpreted to represent fresh-brackish water-saturated volcanic layers at depth beneath this sounding. Sounding L-6 is interpreted to be located above a groundwater damming structure (i.e. dike) in the section and the potential for high-level groundwater may exist beneath this sounding. The exact position of the groundwater barrier is not known due to limited TDEM data in this area of the site.

5.5 HYDROGEOLOGIC INTERPRETATIONS

Table 5-1 contains the approximate thickness of the fresh-brackish water lens calculated from the elevation of the seawater interface interpreted from the TDEM soundings taken at the property. The table includes the value of static water level (head) calculated by using the Ghyben-Herzberg Principle.

Table 5-1 Hydrogeologic Information Derived From TDEM Soundings VILLAGES OF LEIALI'I, KAA NAPALI, MAUI (Values in Feet)				
Sounding Number	Surface Elevation	Elevation of Top of the Conductive Layer	Calculated Static Water Level (Head) Using Ghyben-Herzberg Principle	Approximate Thickness of Fresh-Brackish Water Lens
L-1	1000	-144	3.6	147
L-2	1410	*	*	*
L-3	1440	*	*	*
L-4	1660	*	*	*
L-5	1010	*	*	*
L-6	1660	*	*	*

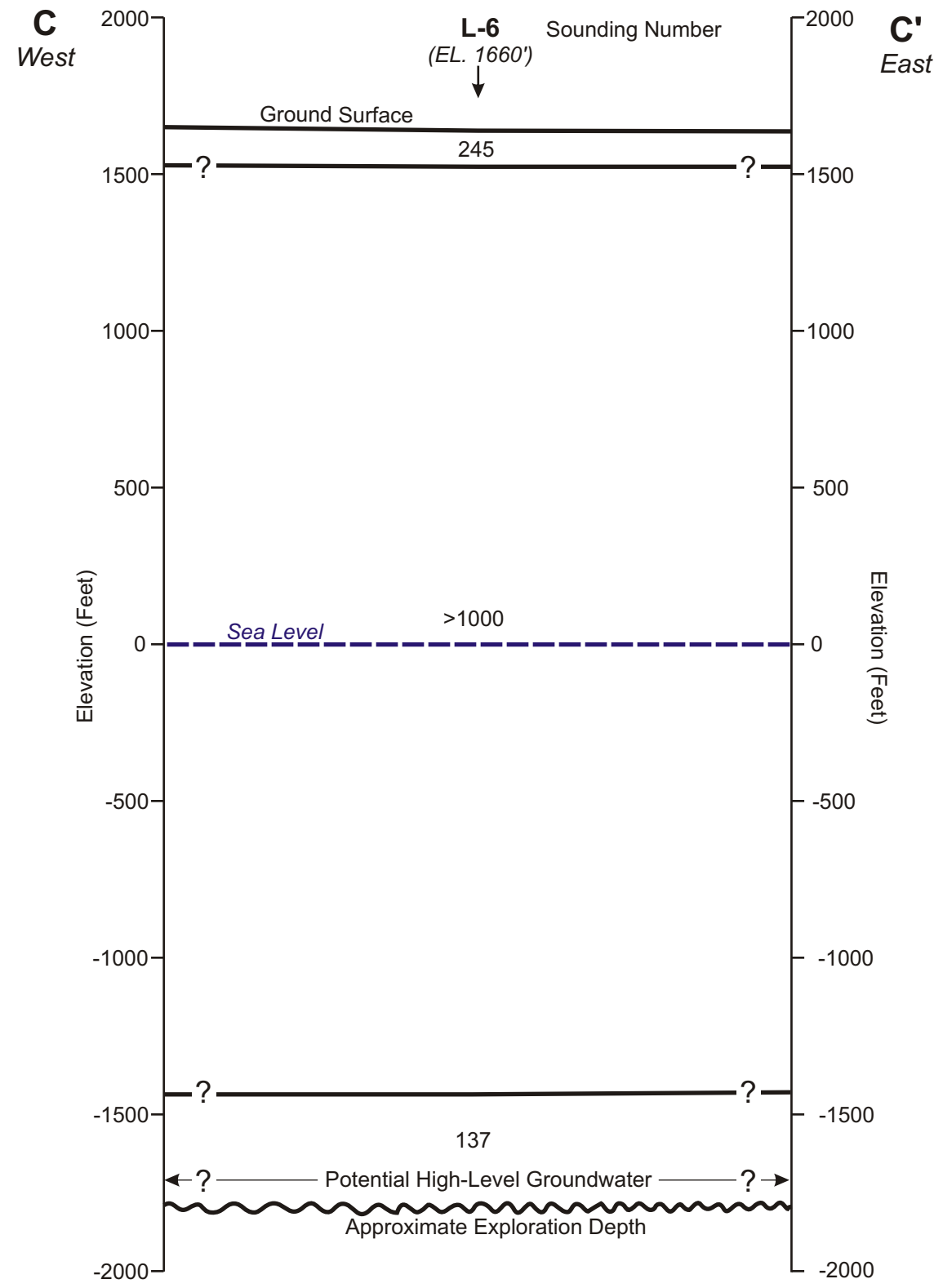
*Sounding in which seawater was not detected.

The TDEM data is further summarized on the interpretation map shown in Figure 5-4. On this map the soundings are color coded as follows:

- Blue-colored soundings detected seawater at depth. The depth to the seawater interface is given (i.e. -144 ft).
- Green-colored soundings are interpreted to be located within areas that have detected intermediate resistivity (20 ohm-m) in which 2-D structures (i.e. dikes, ash flows, etc) have likely distorted the true resistivity values.
- Yellow-colored soundings are located in areas that have potential for high-level groundwater.

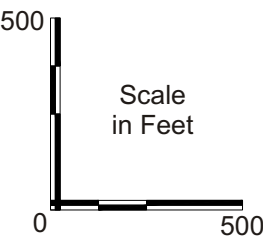
The accuracy of determining the depth to the salt water interface from TDEM soundings is estimated to be +/-5% of the total depth calculated in the sounding measurement (i.e. from the ground surface to the seawater interface).

Line 3



Explanation

- 132 Resistivity (Ohm-m)
- Resistivity Boundary (Dashed Where Uncertain)
- Inferred Lateral Discontinuity
- Laterite Soil (Clay Rich Layer)
- Dry Clay Poor or Fresh-Brackish Water Saturated Volcanics
- Inferred Structure (Possible Ash Falls, Weathered Volcanics or Intrusives)
- Seawater Saturated Volcanics

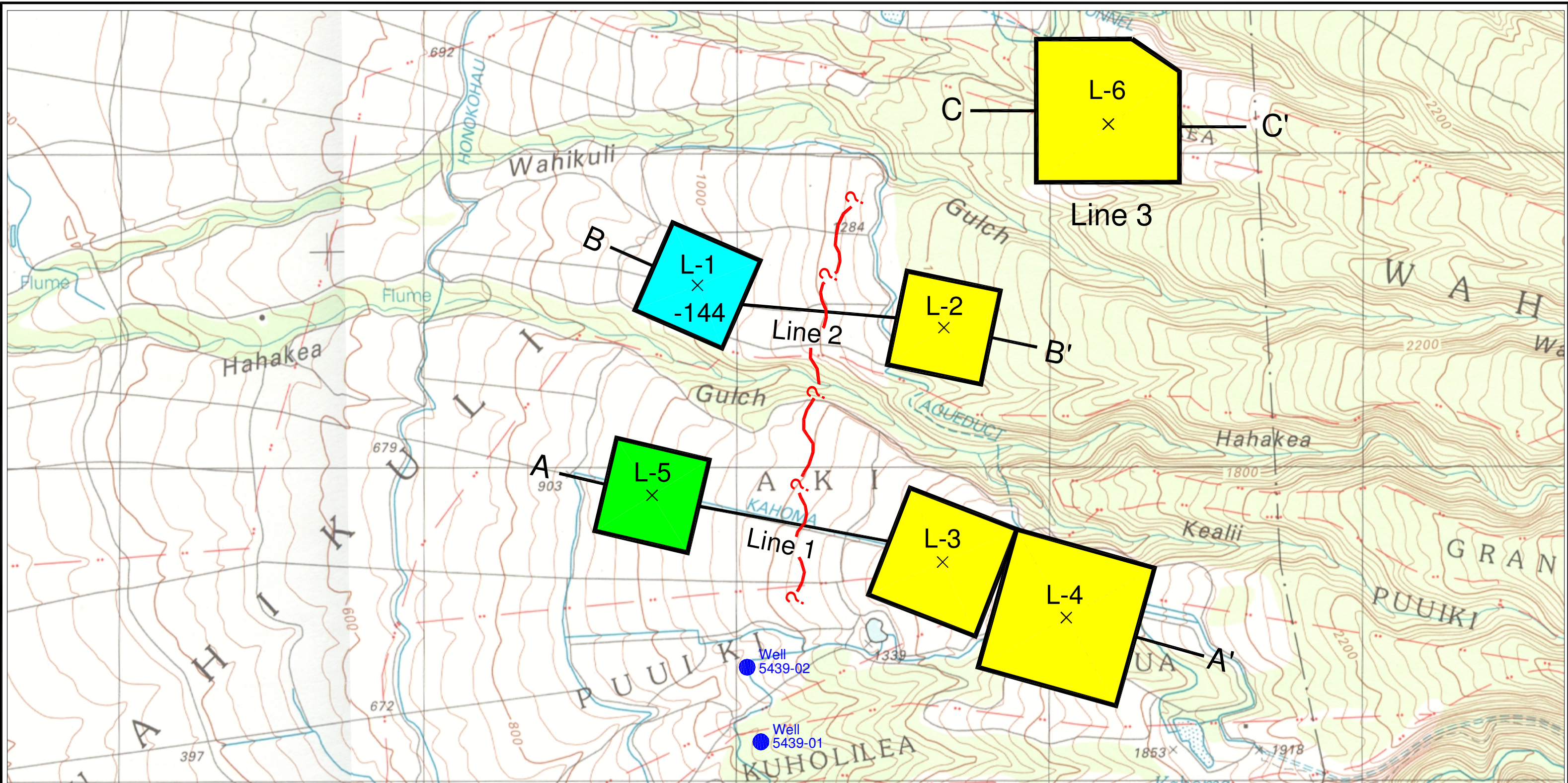


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5156	November, 2009	HJV	RJB	As Shown	5-3

Geoelectric Cross-Section
from 1-D TDEM Inversions
Line 3 - Transect C-C'
Lahaina District
Island of Maui



Explanation

- 144 Approximate Elevation of Top of Salt-Water Interface in Feet
- x Sounding in which Groundwater is expected in basal Mode
- x Sounding Interpreted to be located within Groundwater Barrier (Zone of Change) Data may be distorted by 2-D Geoelectric Structures
- x Sounding in which Groundwater is expected to be controlled by Geologic Structure (Potential High-Level Water)

- ~? Inferred Geologic/Hydrologic Discontinuity (Position and Width Uncertain)
- A-A' Section Line
- Well 5439-02

0 1000 2000
Scale in Feet



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Villages of Leiali'i
Kaanapali, Maui

Project No:
5156

Date:
Nov., 2009

Drawn By:
HJV

Checked By:
RJB

Scale:
1"=1000'

Figure:
5-4

Geophysical TDEM Survey
Summary Interpretation Map
*Lahaina District
Island of Maui*

6.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM surveys on the property was to explore for potential basal and high-level groundwater resources above the town of Kaanapali on the Island of Maui. The optimum locations for basal mode groundwater are expected to occur where the thickest lens of fresh-brackish water is detected floating on seawater. The optimum locations for high-level groundwater are expected to occur above groundwater damming structures (i.e. intrusive, dikes, etc.) detected at relatively low surface elevations.

The results from the TDEM surveys are shown on Figures 5-1 through Figure 5-4 and Table 5-1. The general conclusions and optimum drilling locations interpreted from the TDEM soundings collected on the property are in the following areas:

1. Line 1 - Transect A-A'

- The State Well No. 5439-02 (Wahikuli Well 2) has a reported head of 5.0 ft (per coms T. Nance) and is located about 2,000 ft southeast of Sounding L-5. The data from Sounding L-5 shows an intermediate resistivity (20 ohm-m) layer occurring at a depth of 206 ft bsl in this area. Because seawater was not detected beneath this sounding, a direct comparison of head (using the Ghyben-Herzberg Principle) cannot be made to this well. However, pump test results show that a time-dependent component of the well's drawdown and recovery has a boundary effect. From the data a geologic/hydrologic discontinuity (i.e. 2-D dike structure, etc.) is interpreted in the vicinity of the well, which is likely causing damming of groundwater in this area. The potential for fresh-brackish groundwater appears to exist beneath Soundings L-3 and L-4, with high resistivity layers interpreted to depth of about 955 ft bsl and 1,860 ft bsl, respectively.

2. Line 2 – Transect B-B'

- Beneath Sounding L-1 the basal mode groundwater lens is interpreted to be 147 ft thick. A geologic/hydrologic discontinuity (i.e. 2-D dike structure, etc.) is interpreted between Soundings L-1 and L-2. The potential for fresh-brackish groundwater is anticipated to exist beneath Sounding L-2, with high resistivity layers interpreted to depth of about 1,053 ft bsl.

3. Line 3 – Transect C-C'

- A geologic/hydrologic discontinuity (i.e. 2-D dike structure, etc.) is expected to be located down slope from Sounding L-6 and the potential for fresh-brackish groundwater appears to exist beneath this area with high resistivity layers interpreted to depth of about 1,430 ft bsl.

Additional TDEM soundings located between existing data sets will help to define the extent of basal mode and potential high-level groundwater resources in this portion of the Island of Maui.

7.0 CERTIFICATION AND DISCLAIMER

All geophysical data analysis, interpretations, conclusions, and recommendations in this document have been prepared under the supervision of and reviewed by Zapata Incorporated, Blackhawk Division Senior Geophysicists.

This geophysical investigation was conducted using sound scientific principles and state-of-the-art technology. A high degree of professionalism was maintained during all aspects of the project from the field investigation and data acquisition, through data processing, interpretation, and reporting. All original field data files, field notes and observations, and other pertinent information are maintained in the project files and are available for the client to review.

A geophysicist's certification of interpreted geophysical conditions comprises a declaration of his/her professional judgment. It does not constitute a warranty or guarantee, expressed or implied, nor does it relieve any other party of its responsibility to abide by contract documents, applicable codes, standards, regulations, or ordinances.

Jim Hild

Richard Blohm

Manager/Senior Geophysicist
ZAPATA/Blackhawk Division

Senior Geologist/Geophysicist
ZAPATA/Blackhawk Division



Tom Nance Water
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MAY 21 2008

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be mailed to you.

May 20, 2008
08-122 (07-86)

MEMORANDUM

TO: Alan Kato and BCH
FROM: Tom Nance
SUBJECT: Evaluation of the Pump Test Results of Wahikuli Well 1,
State No. 5439-01

This memo and its attachments will summarize the pump test data and my interpretations of it for Wahikuli Well 1, State No. 5439-01. The well was constructed to State Department of Land and Natural Resources (DLNR) standards and the pump test was run by Mitch Ouye at DLNR, so I am confident that construction methods were satisfactory and that the pump test data are reliable.

Pump Tests

The initial pump test was run on March 30 to 31, 1992. It was interrupted and then finally stopped due to equipment malfunction. The final pump test was run after the malfunction was corrected from March 31 to April 3, 1992. The initial test did provide the hydraulic performance data presented below and illustrated on Figure 1.

Step-Drawdown Data	
Pumping Rate (GPM)	Drawdown (Feet)
327	4.40
502	7.55
675	12.20

Fitted Curve

$$S = AQ^2 + BQ$$

where: S = Drawdown in Feet
 Q = Pumping Rate in GPM
 $A = 1.326 \times 10^{-5}$
 $B = 8.874 \times 10^{-3}$
 $r^2 = 0.967$

These initial test data established the following several quite anomalous results:

- Based on the well's static water level of 6.6 feet (MSL), the expectation was that it tapped basal groundwater. However, the response to pumping was not typical for basal groundwater. There was a time-dependent component of drawdown and recovery indicative of drawing water from a small compartment created by unknown subsurface geology. Two and a half hours after pumping was stopped, the recovered water level was still 2.6 feet below the initial static level (refer to Figure 2).

- Chlorides were anomalously low (about 12 MG/L) and not sensitive to pumping. As with the time-dependent drawdown and recovery, this suggests that water was drawn from a compartment.
- Drawdown was relatively high. At 675 GPM, for example, it was 12.2 feet.

The second pump test was started on March 31st before full recovery from the first test was achieved. It was run for 70 hours at a reasonably constant 700 GPM rate. Results of this test (on Figure 3) show far more definitely the time-dependent, compartmentalized groundwater response: drawdown continued to increase throughout the test; a stable drawdown level was never achieved; recovery was slow; and after six hours, the recovered water level was still 6.55 feet below the original static level.

Time-dependent drawdown and recovery are more appropriately evaluated on a semi-log plot such as Figure 4. This shows that a clear boundary effect occurred about 1000 minutes into the 4200-minute test, resulting a substantial steepening of the drawdown rate. Recovery is plotted from right to left on the graph (the X-axis is the time since pumping started divided by the time since pumping stopped). It typically duplicates the drawdown curve, offset above it by the turbulent component of drawdown. Measuring water levels by slow-responding airline may be the reason the "duplication" of the recovery curve is a bit off.

Water Quality

Despite the well's substantial drawdown, there was no salinity increase at any time during the two pump tests (chlorides were consistently about 12 MG/L). Complete drinking water analyses were done by Montgomery Laboratories (Sample No. 930121033) on a January 19, 1993 sample, some nine months after the contractor's pump test and apparently using a pump installed by the Department of Water Supply (DWS) for the sampling. Results showed the water to be of excellent quality.

Issues and Recommendations

1. DWS has an unwritten (and for some situations, questionable) policy of not allowing the well's drawdown to drop below mean sea level. In this instance, such a policy would limit the capacity of the permanent pump to less than 450 GPM. I have no information on the capacity of the pump now installed in the well, but it is highly unlikely that it is salvageable after more than a decade of not being run. Plans completed by Unemori called for a 400 GPM submersible pump to be used.
2. I believe this well has a long-term useable safe capacity, but that capacity is probably in the range of 300 GPM. A pump test at that rate would need to be conducted to confirm that. Pumping for a minimum of seven days and possibly longer would be needed. At the end of that time, resampling for DOH drinking water certification could be done.
3. Assuming the intention is to dedicate this system to DWS, agreements with that agency should be obtained before undertaking a costly pump test.

Attachments

**Figure 1. March 30, 1992 Step Test Performance
of Wahikuli Well 1 (5439-01)**

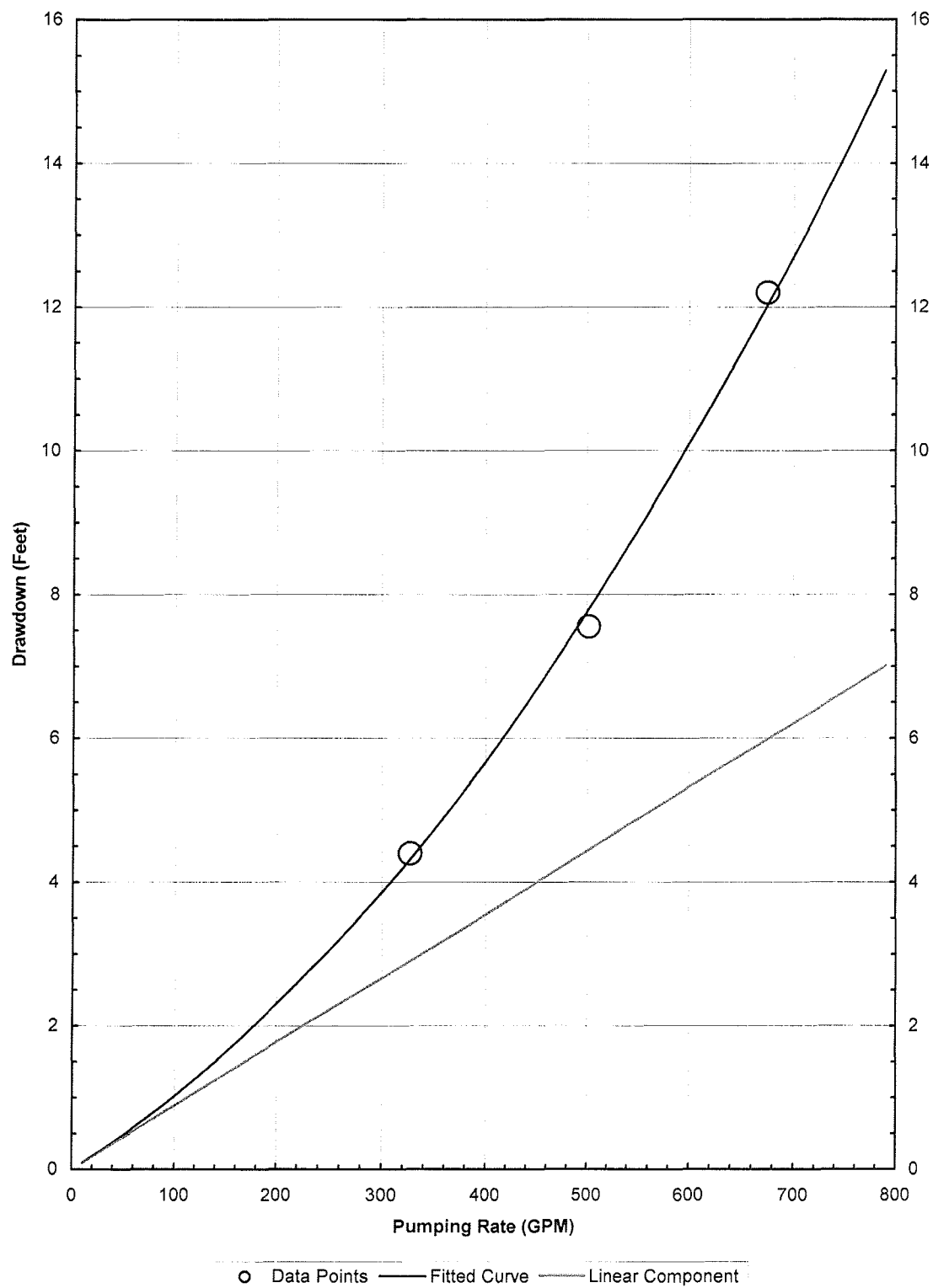


Figure 2. Linear Plot of the First Pump Test
of Wahikuli Well 1, March 30 to 31, 1992

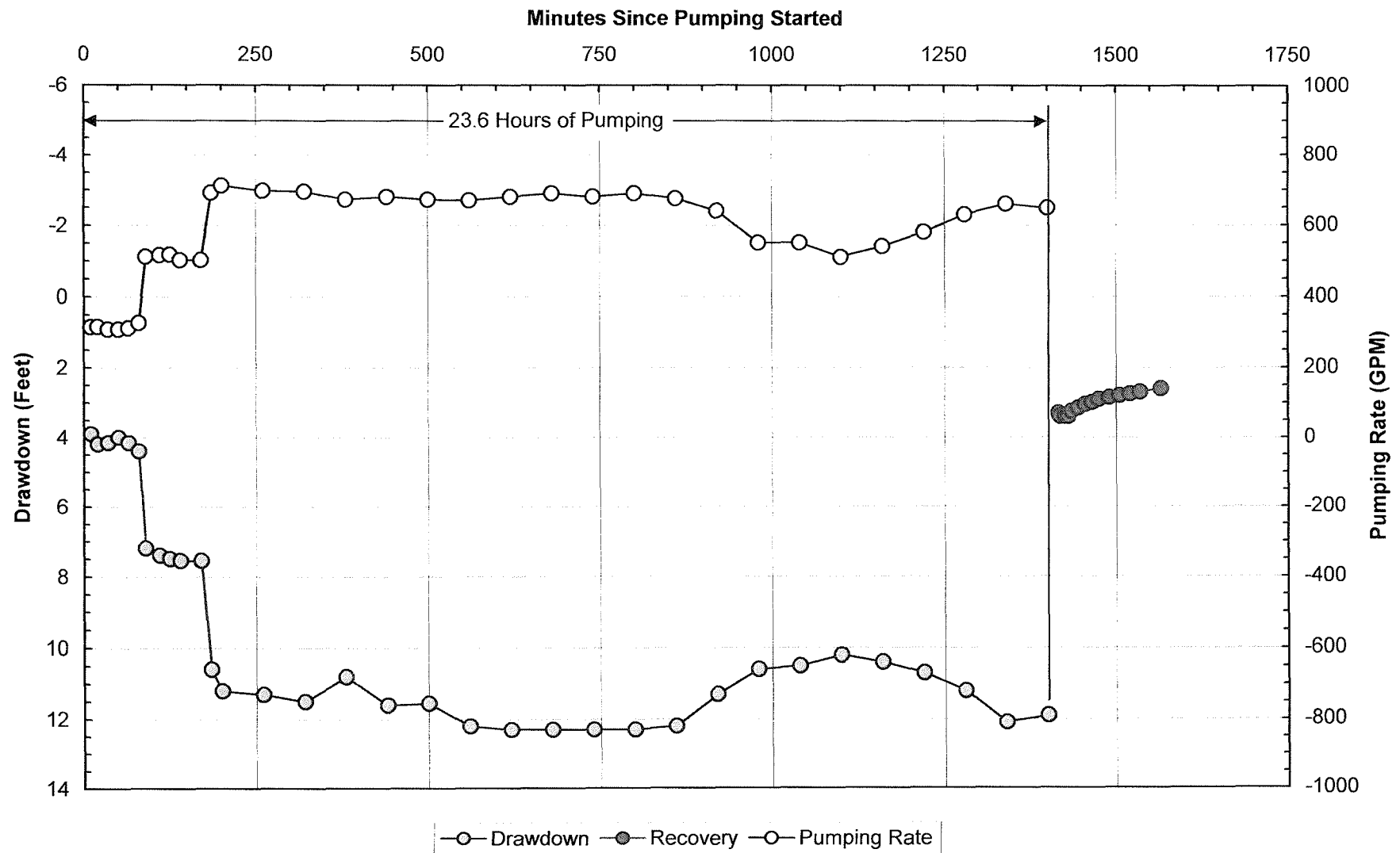


Figure 3. Linear Plot of the Second Pump Test
of Wahikuli Well 1, March 31 to April 3, 1992

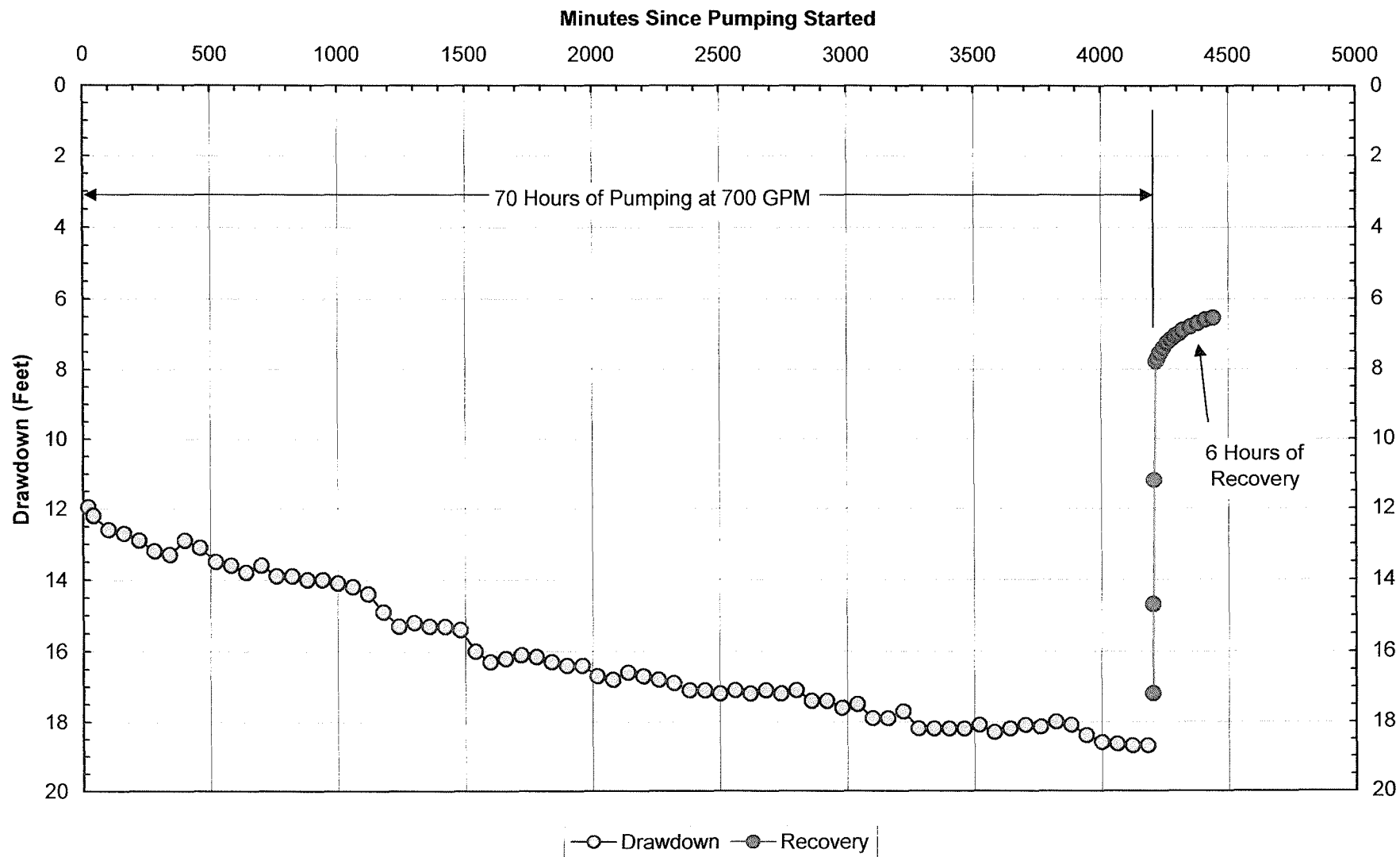
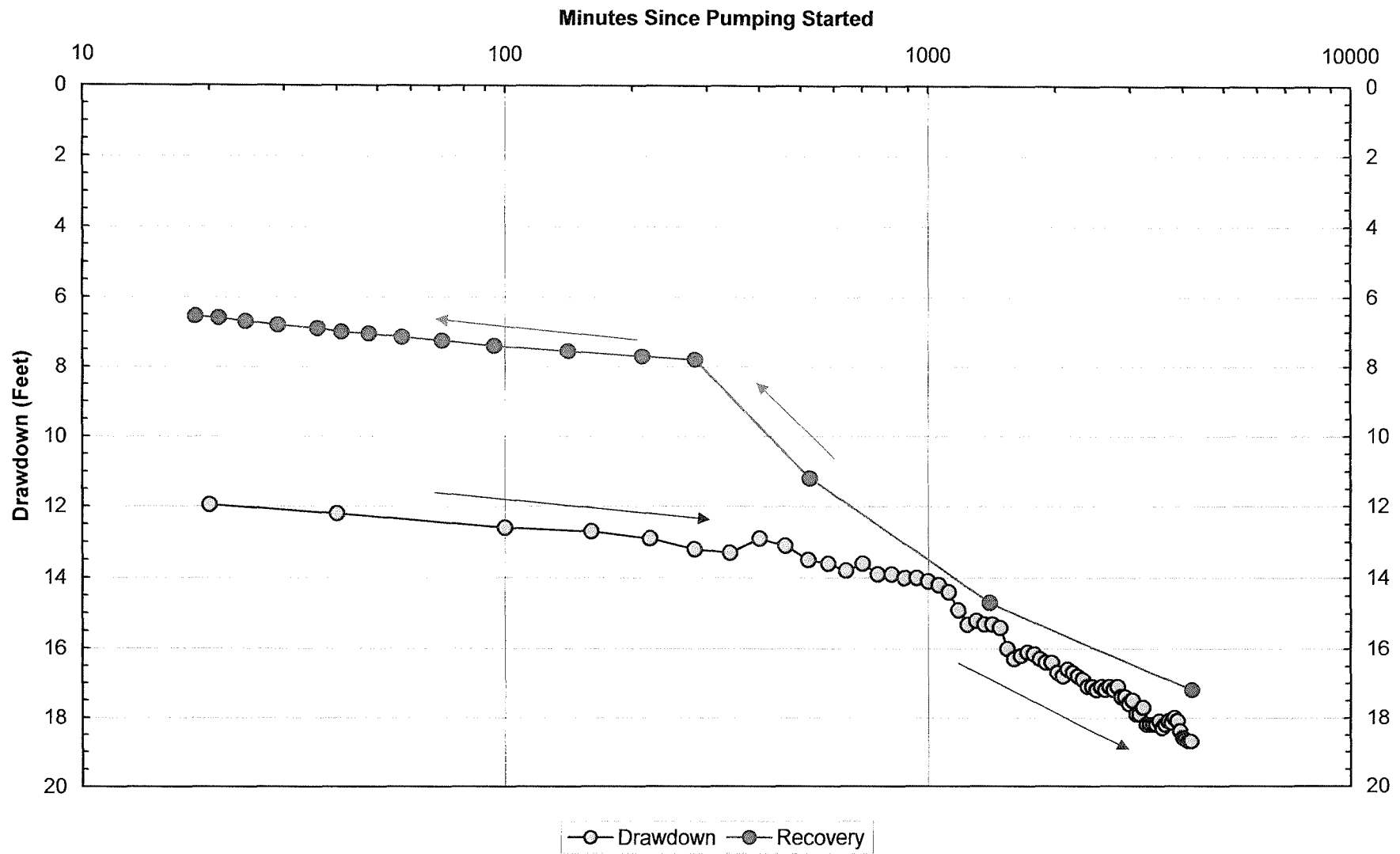


Figure 4. Semi-Log Plot of the Second Pump Test
of Wahikuli Well 1, March 30 to April 3, 1992





Tom Nance Water
Resource Engineering

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MAY 27 2008

May 27, 2008
08-133 (07-86)

MEMORANDUM

TO: Alan Kato - BCH
FROM: Tom Nance
SUBJECT: Evaluation of the Pump Test Results of Wahikuli Well 2,
State No. 5439-02

This memo and its attachments summarize the results and my interpretations of the pump test of Wahikuli Well 2, State No. 5439-02. This well was constructed by Water Resources International, Inc. (No. 1 was done by Paul Frandsen). As with Well 1, the pump test was run by Mitch Ouye of the State Department of Land and Natural Resources.

Pump Tests

Two pump tests were run, a step-drawdown test on June 25, 1993 and then a 120-hour constant rate test from June 28 to July 3, 1993. Their results are described below.

Step-Drawdown Pump Test. The step-drawdown test defined the well's very substantial hydraulic capacity, a consequence of the highly permeable lavas the well penetrates (refer to the tally below and Figure 1). Drawdown was only 2.3 feet at 1000 GPM, for example. Well 2's capacity is far greater than Well 1 which, at a drawdown of 2.3 feet, would only be producing about 200 GPM.

Step-Drawdown Data	
Pumping Rate (GPM)	Drawdown (Feet)
394	0.60
617	1.20
750	1.50
1014	2.30

Fitted Curve

$$S = AQ^2 + BQ$$

where:

- S = Drawdown in Feet
- Q = Pumping Rate in GPM
- A = 1.157×10^{-6}
- B = 1.131×10^{-3}
- $r^2 = 0.946$

Constant Rate Pump Test. The five-day constant rate pump test was run at an average of 1016 GPM (Figure 2). Two key indicators of the well's long-term performance were demonstrated. First, there was a time-dependent component of the well's drawdown and recovery with an obvious boundary effect.

This is not like the typical response of basal groundwater in a formation as permeable as shown by the step-test results. The semi-log plot on Figure 3 best illustrates this. Second, although chlorides were quite low (between 20 and 30 MG/L), they steadily increased throughout the five-day test (Figure 2).

Conclusions and Recommendations

1. The boundary effect which manifested itself as a steepening of the drawdown curve 120 minutes into the constant rate test was caused by an unknown subsurface feature. It undoubtedly contributed to the exceptionally low salinity of the pumped water.
2. Continuously increasing chlorides during the constant rate test demonstrated that the test's 1000 GPM rate clearly exceeded the well's long term yield.
3. In view of the pump test results and the size of the upgradient contributing watershed, I would limit the installed pump capacity to 450 GPM.
4. I could not find any laboratory analyses of regulated drinking water constituents and I suspect no such sampling was ever done. Certification of the well by DOH-SDWB will require installation of a pump, sampling, and laboratory analyses of the samples.

Attachments

**Figure 1. June 25, 1993 Step Test Performance
of Wahikuli Well 2 (5439-02)**

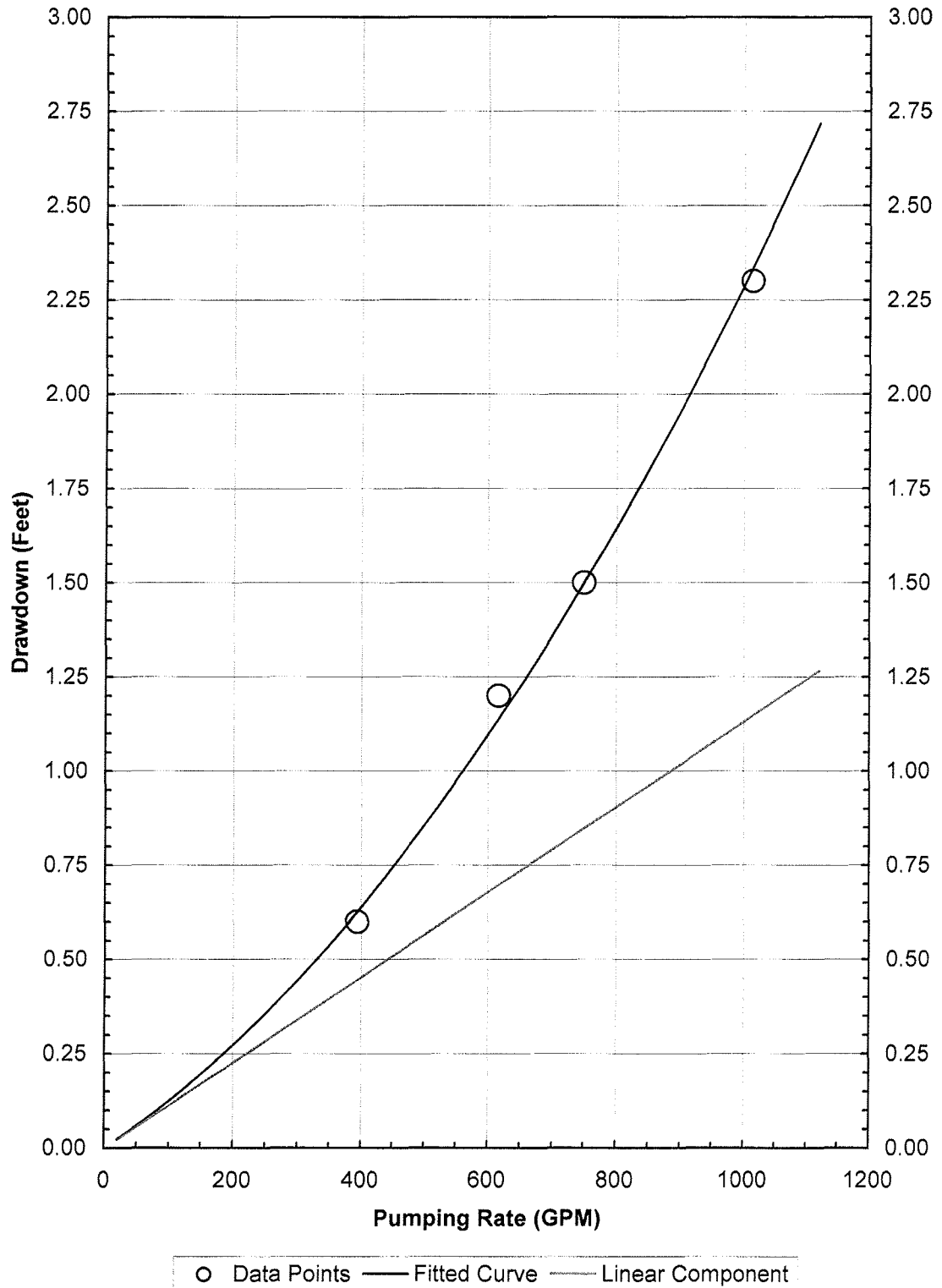


Figure 2. Chlorides During the 1000 GPM Constant Rate Pump Test of Wahikuli Well 2 (State No. 5439-02)

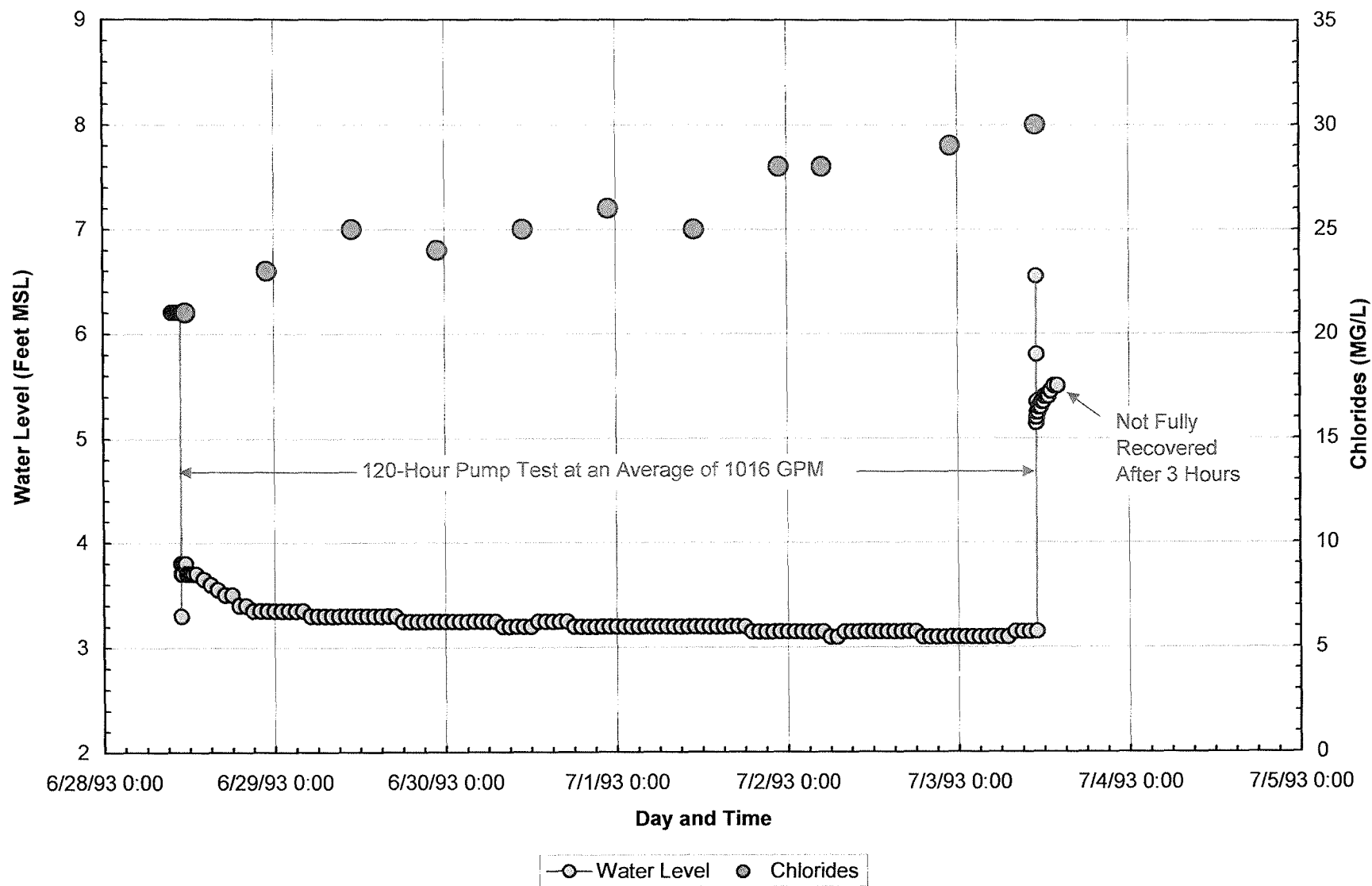
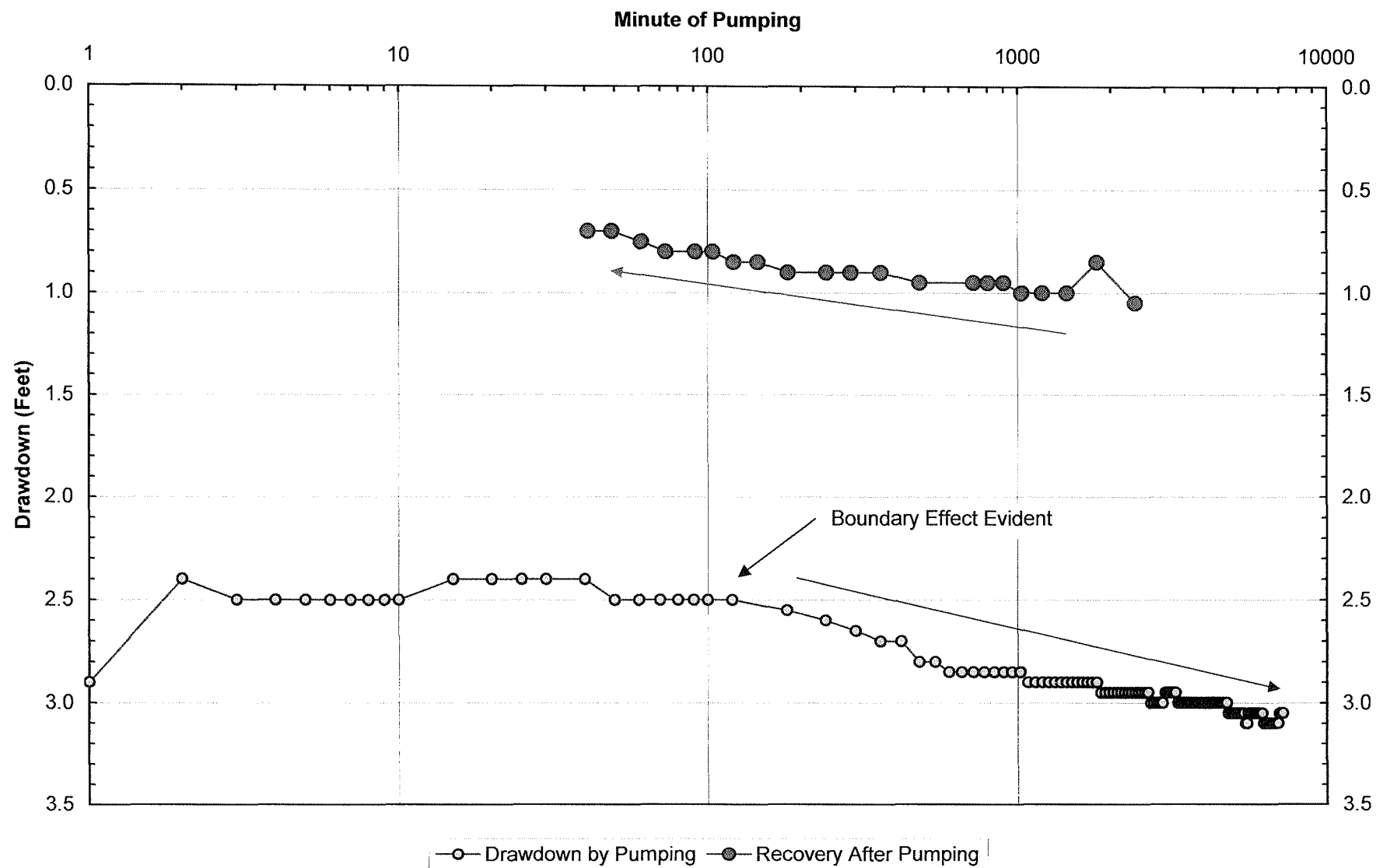


Figure 3. Drawdown and Recovery During the Constant Rate Pump Test of Wahikuli Well 2



Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics

Pieter Hoekstra and Mark W. Blohm**

Abstract

Time-domain electromagnetic (TDEM) soundings are a surface electromagnetic technique that finds increasing use in environmental geophysics. Commercial equipment is now available for TDEM soundings in the exploration depth range from about 5 m to about 5000 m. Application of TDEM is illustrated in three case histories.

The transmitter-receiver array used in all three investigations was the central-loop array, in which measurements of the electromotive force due to the vertical magnetic field are made with a receiver in the center of square, nongrounded transmitter loops. The dimensions of the transmitter loops were varied from 30 m by 30 m for effective exploration depths between 5 m to 75 m, to 500 m by 500 m for effective exploration depths to about 2500 m. These relatively small dimensions of receiver/transmitter arrays, compared to the exploration depth, allow TDEM surveys to be made in urban areas where open spaces are limited in size, and where environmental and ground-water problems are perhaps most urgent. Also, the procedures of signal processing used in TDEM facilitate operation in the presence of high ambient electrical noise prevalent in urban settings.

The three case histories map:

- (1) the depth of first occurrence of brine for assisting site evaluation of a high-level nuclear-waste repository in bedded salts near Carlsbad, New Mexico,
- (2) the encroachment of salt water in a multiple-zone coastal aquifer system in the Salinas Valley, California, (The availability of about 100 monitoring wells allowed correlation of formation resistivities to ground-water salinity.) and

- (3) shallow basalt flows in the exploration depth range from 5 m to 30 m. (This case history shows the results of TDEM measurements over the time range from about 10^{-6} s to 10^{-4} s with central-loop soundings of small (30 m) dimensions.)

Introduction

Time-domain electromagnetic (TDEM) soundings increasingly are being employed for determining geoelectrical sections. Reported applications of this TDEM method are in mapping of volcanic cover (Frischknecht and Raab, 1984; Keller et al., 1984), onshore and offshore permafrost (Ehrenbard et al., 1983), geothermal reservoirs (Fitterman et al., 1988), hydrocarbons (Rabinovich et al., 1977; Wightman et al., 1983), and ground water (Fitterman and Stewart, 1986; Mills et al., 1988). Theoretical aspects of the method, such as behavior of magnetic and electric fields (e.g., Nabighian and Oristaglio, 1984), definition of apparent resistivity (Kaufman and Keller, 1983; Spies and Eggers, 1986), transmitter-receiver arrays (Kaufman and Keller, 1983), and influence of two-dimensional (2-D) and three-dimensional (3-D) structures on one-dimensional interpretations (Hohmann, 1988; Newman et al., 1987) are discussed throughout the geophysical literature [see also McNeill, Vol. I—Ed.].

Several reasons are apparent for the increasing use of TDEM in environmental geophysics. In urban areas ambient electrical noise is high, and open spaces limited. TDEM surveys can often work around these limitations. Small transmitter-receiver arrays can be laid out in athletic fields, parks, and other open spaces, and ambient

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electrical noise due to residential power service can often be removed by stacking. Also, recent availability of equipment with fast, current ramp turn-off and early-time measurements bring shallow mapping objectives for ground-water protection and contaminant investigations within the exploration depth range of TDEM.

A limitation of TDEM at this time is the lack of practical, cost-effective algorithms for interpreting 2-D and 3-D structures. At present, forward modeling of 2-D and 3-D structures (Newman et al., 1987), requires significant central processing unit (CPU) time on the mainframes negating their application to shallow TDEM exploration. It is in the development of practical algorithms for 2-D and 3-D interpretations for personal computers that the main advances in TDEM must come.

Illustrated applications of the method to three environmental objectives include (1) assisting in siting of high-level, nuclear-waste repositories, (2) mapping the intrusion of salt water in coastal aquifers, and (3) mapping the thickness of thin basalt flows. The basic principles of the equipment and the procedures of data acquisition and processing are similar for all three case histories. Some characteristics of central-loop array measurements, such as land survey requirements, location of plotting points, and vertical resolution are reviewed briefly. Equipment design parameters and data acquisition, processing, and interpretation procedures are discussed. These principles are illustrated subsequently on the three case histories. The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories.

Practical Aspects of Data Acquisition

Transmitter-Receiver Arrays

The three types of transmitter-receiver arrays employed in TDEM soundings are illustrated in Figure 1. The array used in the three case histories is the central loop array (Figure 1b). For applications in environmental geophysics there are certain advantages to the central loop array, such as:

(a) **Land survey and space requirements.**—Figure 2 shows the measured behavior of the electromotive forces (emf's) due to horizontal (x) and vertical (z) magnetic field components on a profile through the center of a square transmitter loop at 2.2 ms after current turn-off. Data at other times would show a similar behavior but differ in amplitudes. The emf due to the z -component can be seen to be relatively flat about the center. Location errors of $\pm 10\%$ L (L is side of square) cause neg-

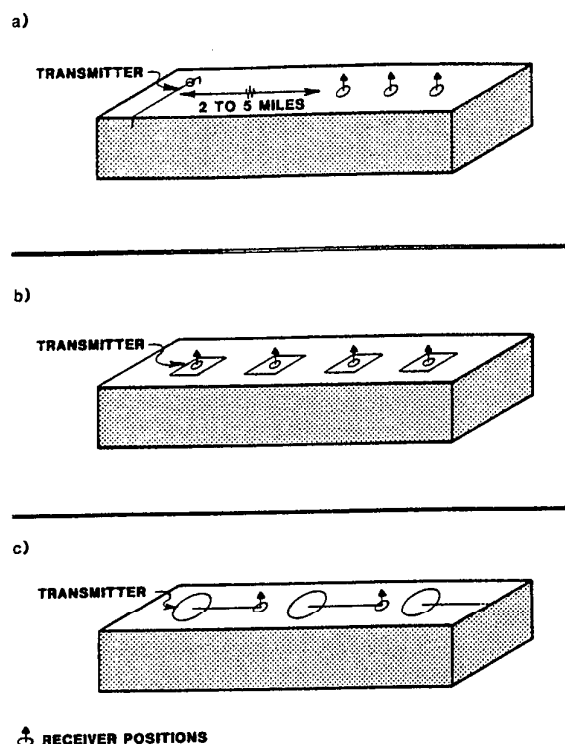


FIG. 1. Transmitter-receiver arrays, (a) grounded line, (b) central loop, and (c) loop-loop.

ligible errors, and deviations from a square transmitter loop have little effect on a data set. Because in central loop soundings the geoelectric section is derived from emf_z , requirements for accurate positioning are minimal which enhances the practical value of field survey productivity, and allows flexibility in choosing a station location. Because emf_z has a zero crossing in the center of the loop, its measurement would require careful survey control. Also, ambient electrical noise is higher in horizontal components.

The dimensions of transmitter loops in central-loop arrays depend on required exploration depth, exploration objective, and geoelectric section. Optimum dimensions are generally selected from forward modeling and field tests. Typically, the length of a side of the transmitter loop is about two-thirds of the exploration depth for the EM-37. The EM-42 is generally employed for exploration depths from about 300 m to 2500 m with 500 m by 500 m transmitter loops, and with a grounded line array for deeper objectives.

The grounded line array (Figure 1a) with long offset receiver locations is dominantly used in deep electrical soundings in support of oil and gas exploration (Keller et al., 1984). The loop-loop array (Figure 1c) finds ap-

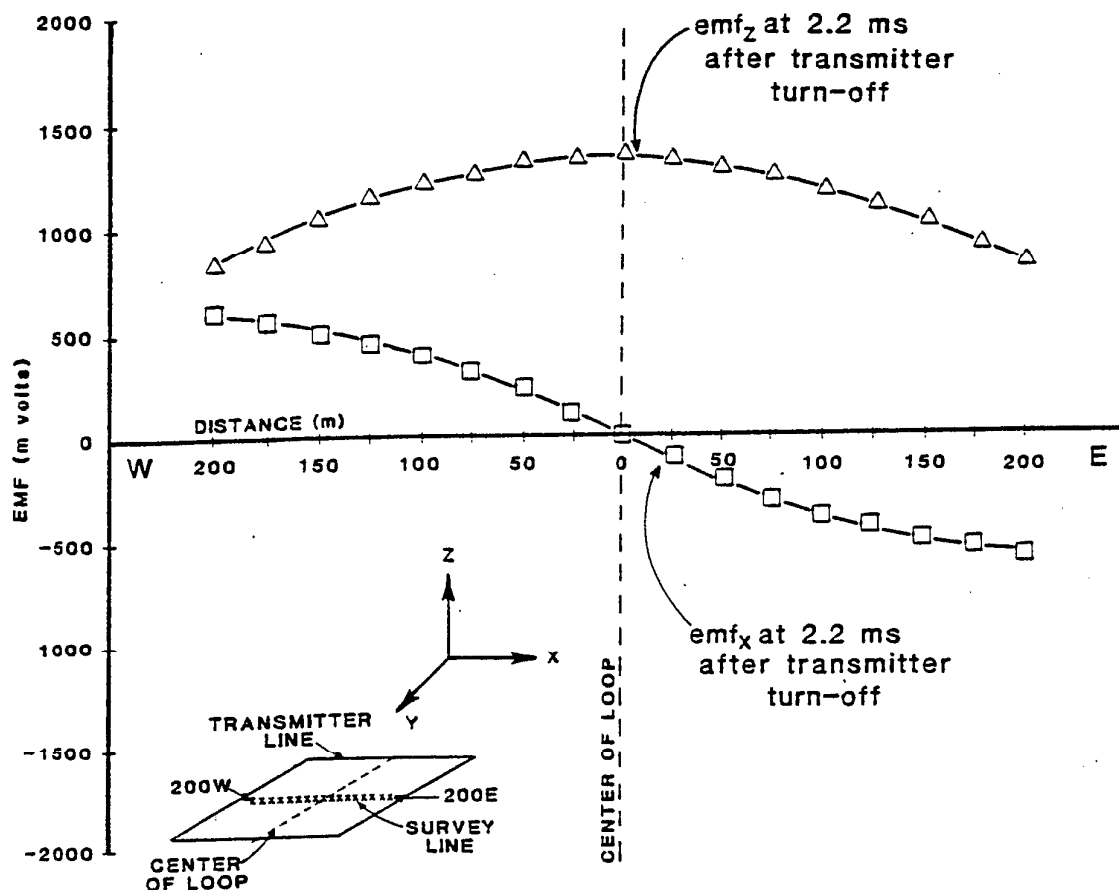


FIG. 2. Measured behavior of the electromotive forces due to vertical (emf_z) and horizontal (emf_x) magnetic fields on a profile through the center of a square transmitter loop.

plication in mineral exploration and in mapping of fractures and shear zones.

(b) **Well-defined sounding plotting points.**—The behavior of induced eddy currents and the resulting behavior of the secondary magnetic fields in horizontally-layered media are well documented (Kaufman and Keller, 1983; Ward and Hohmann, 1988). They show a current distribution diffusing downward and outward from the source. For nongrounded, square-loop transmitters currents are symmetrically distributed about the center. Therefore, the center is a well-defined plotting point.

In the grounded-line array or loop-loop array the entire section between transmitter and receiver is expected to influence the measurements, although subsurface conditions near the receiver may have a larger influence on emf_z measured. The correct plotting point of a station is not well defined. Some place the plotting point below the receiver (Keller et al., 1984) and others midway be-

tween the transmitter and receiver (Rabinovich and Surkov, 1978). This same situation prevails in loop-loop arrays. In frequency-domain loop-loop arrays the midpoint of the array has traditionally been used as the plotting point.

(c) **Vertical resolution.**—Kaufman and Keller (1983) show that (1) the asymptotic behavior of emf_z at late time, is given by

$$emf_z = \frac{\mu^{5/2} \sigma^{3/2} M_t M_R}{4\pi^{3/2} t^{5/2}}, \quad (1)$$

where

- t = time after current turn-off,
- σ = conductivity of uniform half-space,
- μ = magnetic susceptibility,
- M_t = moment of transmitter,
- M_R = moment of receiver;

and (2) that this asymptotic expression describes the emf over the time range given by;

$$\frac{\tau}{R} > 16, \quad (2)$$

where

$$\tau \text{ is } \sqrt{\frac{8 \pi^2 t}{\mu_0 \sigma}}$$

Figure 3 is a nomograph showing the onset of "late stage" behavior ($\tau/R > 16$), as a function of resistivity, and time at several values of R . Also shown on Figure 3 are the time ranges of measurement for the three systems used in the case histories. In central loop soundings typical values of R are between 15 m and 250 m, so that over a large time range of measurements emf_z is proportional to $\sigma^{3/2}$. This high sensitivity of the quantity measured (emf_z) to the geoelectric section often results in a reduced range of equivalence for certain sections compared to other electrical and electromagnetic techniques (Fitterman et al., 1988).

Equipment

The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories. All three sets of equipment use the current waveform illustrated in Figure 4, consisting of equal periods of time-on and time-off. Figure 5 illustrates the difference in data acquisition between the EM-47 and EM-37, and the EM-42. In the EM-47 and EM-37 an analog stack is performed, and after completion of the stacking and A/D conversion, the data are stored in solid state memory. Normally, at the completion of a survey day, the data are transferred to a computer for data processing, plotting, and interpretation. During field operations no real-time processing is available. Minimum detectable signal in typical, urban, ambient-noise environments is 10^{-9} V/A-m² (normalized by current in transmitter loop, and effective area of receiver coil).

In the EM-42 the transient is sampled at 400 μ s intervals, and these samples are digitally stored on 1/2-inch, 9-track tape. "Smart stacking" is applied to the data in real time. The minimum detectable signal with

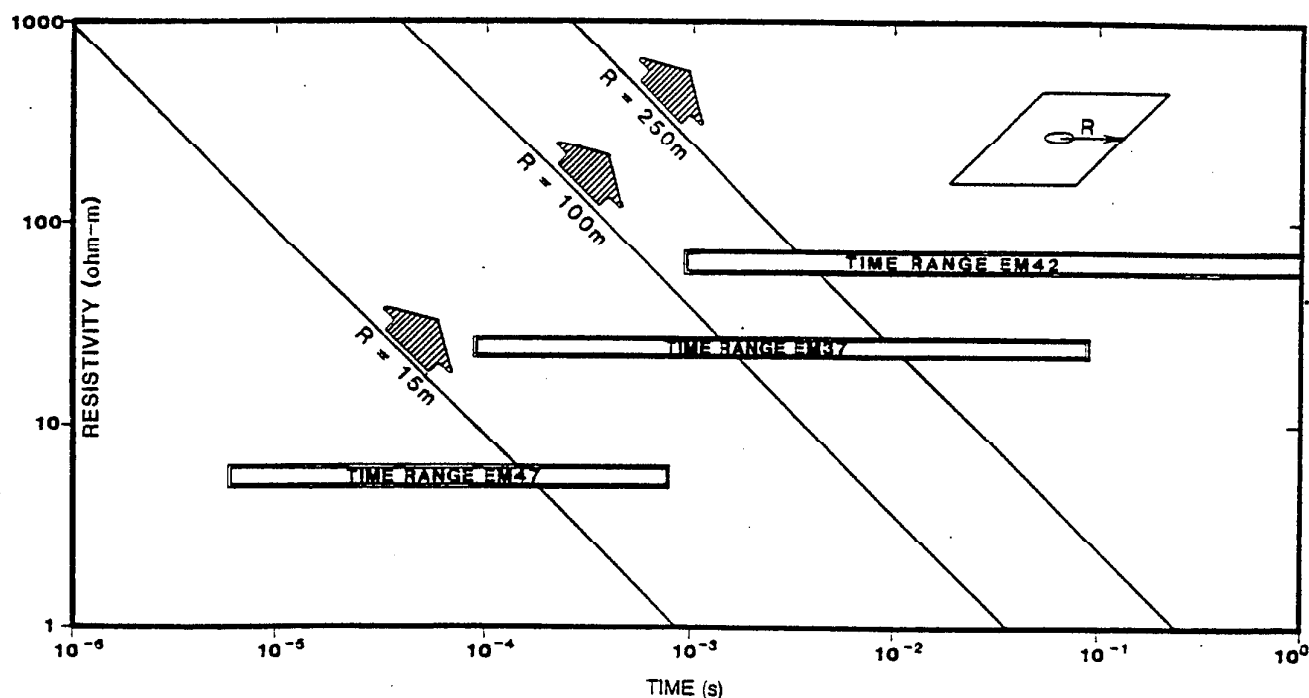


FIG. 3. Nomograph showing onset of late stage behavior for central-loop array as a function of time and resistivity of uniform half-space.

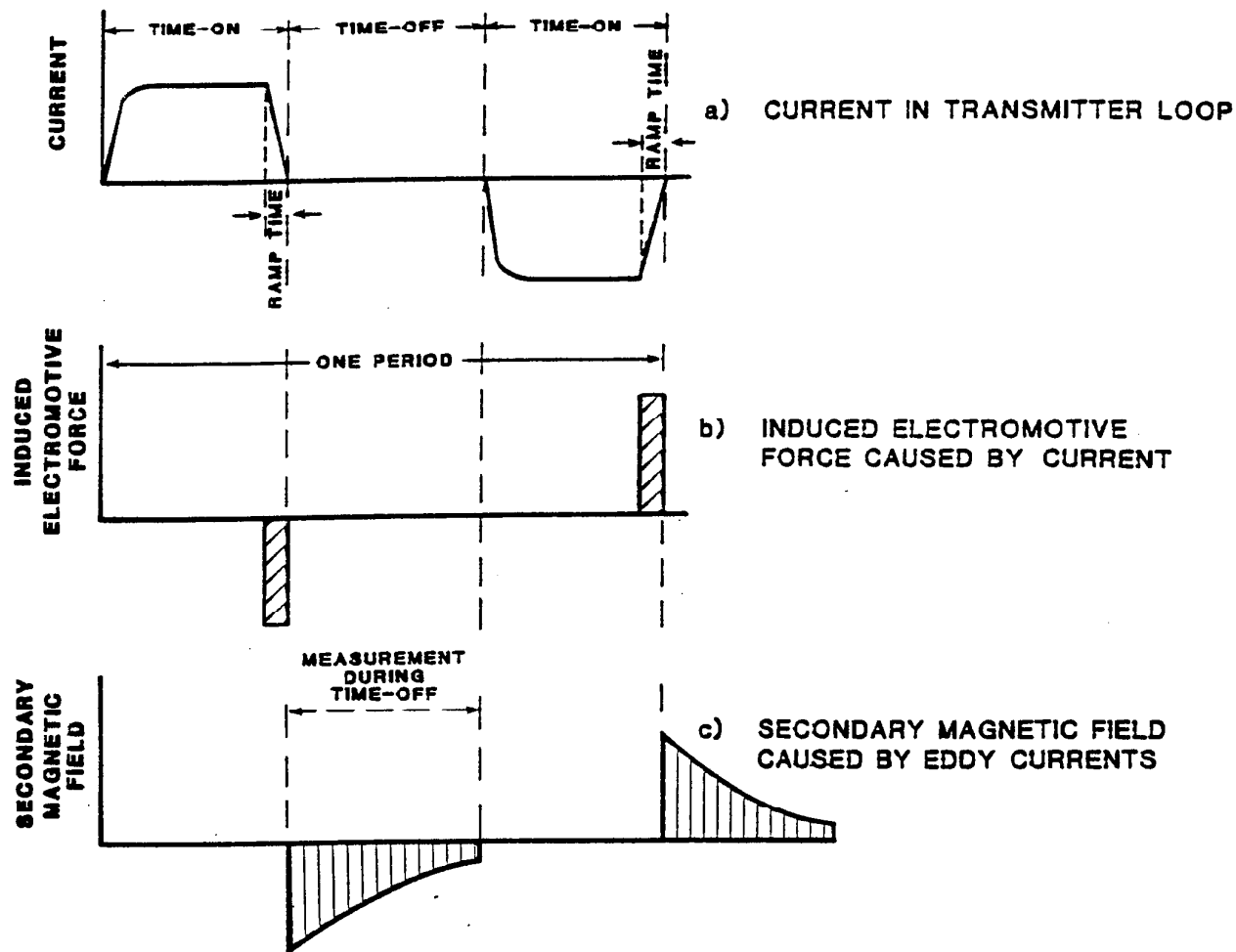


FIG. 4. System waveforms employed in Geonics EM-47, EM-37, and EM-42.

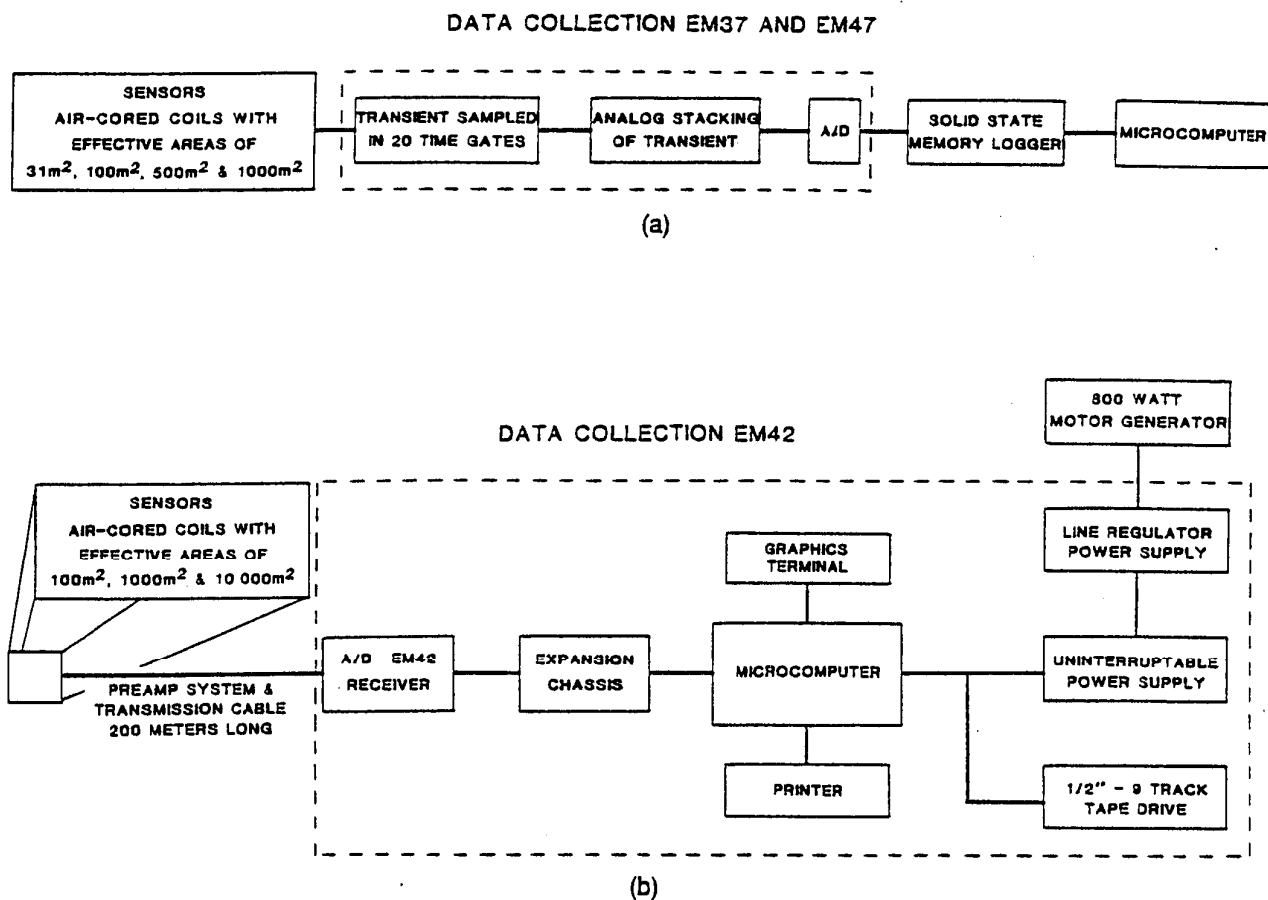


FIG. 5. Block diagrams of TDEM systems.

the EM-42 in typical ambient noise environments is 10^{-12} V/A-m²

Data Acquisition

Recording transient decays with central loop soundings requires a large dynamic range, because emf_i decays as $t^{-3/2}$, as shown in equation (1). This large dynamic range is often obtained by acquiring a data set in segments using different combinations of base frequencies, gains, and air coil receivers. An example of such a data set is given in Figure 6. The early time part of the curve was acquired at a base frequency of 3 Hz, 100 m² air coil and EM-37 receiver; the later time section was recorded with the EM-42 receiver, a 10 000 m² air coil and a base frequency of 0.075 Hz. When the 10 000 m² coil is used, the early time segment of this curve is purposely saturated. It is common to collect data sets at two receiver polarities, various gain settings, base frequencies, and with receiver coils of different effective areas. These various data sets are combined in one transient-decay curve that is subsequently entered into inversion routines.

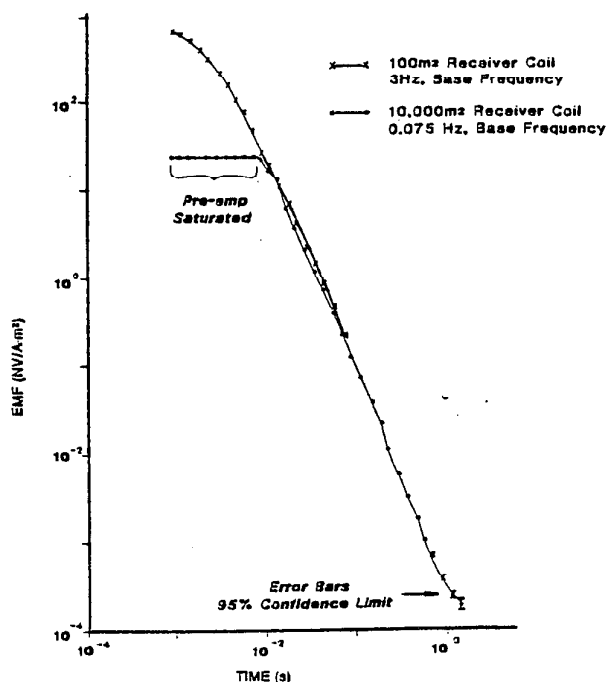


FIG. 6. Emf_i measured in center of 500 m by 500 m transmitter loop.

Definition of Apparent Resistivity

All electrical and electromagnetic methods commonly transform the voltages or emf's measured into apparent resistivities. In TDEM several definitions of apparent resistivity are in use (Kaufman and Keller, 1983; Goldman, 1988) and the merits and pitfalls of the various definitions have been reviewed in Spies and Eggers (1986). These pitfalls are often avoided by (1) integrating inversions with available geologic data, and (2) using albums of forward-model curves for first-guess solutions. In all the case histories late-stage (Kaufman and Keller, 1983) apparent resistivity curves are used. Two reasons for that selection were (1) over a large range of time late-stage behavior is observed in central-loop soundings, and (2) extensive volumes of late-stage model curves (Goldman and Rabinovich, 1974) are available.

Data Interpretation

All the examples shown in the case histories were interpreted by one-dimensional (1-D) inversions of the data using a ridge-regression inversion program (ARRTI, Interpex Ltd, 1985). The input for the program are the emfs measured in various time gates, certain equipment and survey parameters (transmitter loop size, current, ramp time, receiver coil effective area), and number of layers to be used in the inversion. Also, an initial solution is entered. Goldman (1988) discussed the dependence of inversion routines on this first guess. To mitigate convergence to unrealistic solutions, first guesses are made to correspond with known geologic conditions, and depending on the quality of available geologic information, certain parameters in a geoelectric section may be fixed at specific values, e.g., as observed in borehole logs.

In TDEM soundings there is merit in carefully considering inversion errors at each time gate, because each section of the curve is often diagnostic of a certain depth section (Kaufman and Keller, 1983; Raiche and Gallagher, 1985). This can be illustrated by a central loop TDEM sounding with a 500 m by 500 m transmitter loop over a Tertiary valley fill in Nevada. Figure 7b shows the late-stage, apparent resistivity curve and Figure 7a two 1-D inversions for this sounding. The difference between the two inversions is the absence of a resistive layer (basalt flow) in section 1, and its presence in section 2. Figure 7c shows the error between the measured data and the two inversions. The increased error over the early time range suggested inserting an additional layer into the inversion. The existence of this resistive layer has been confirmed by drilling.

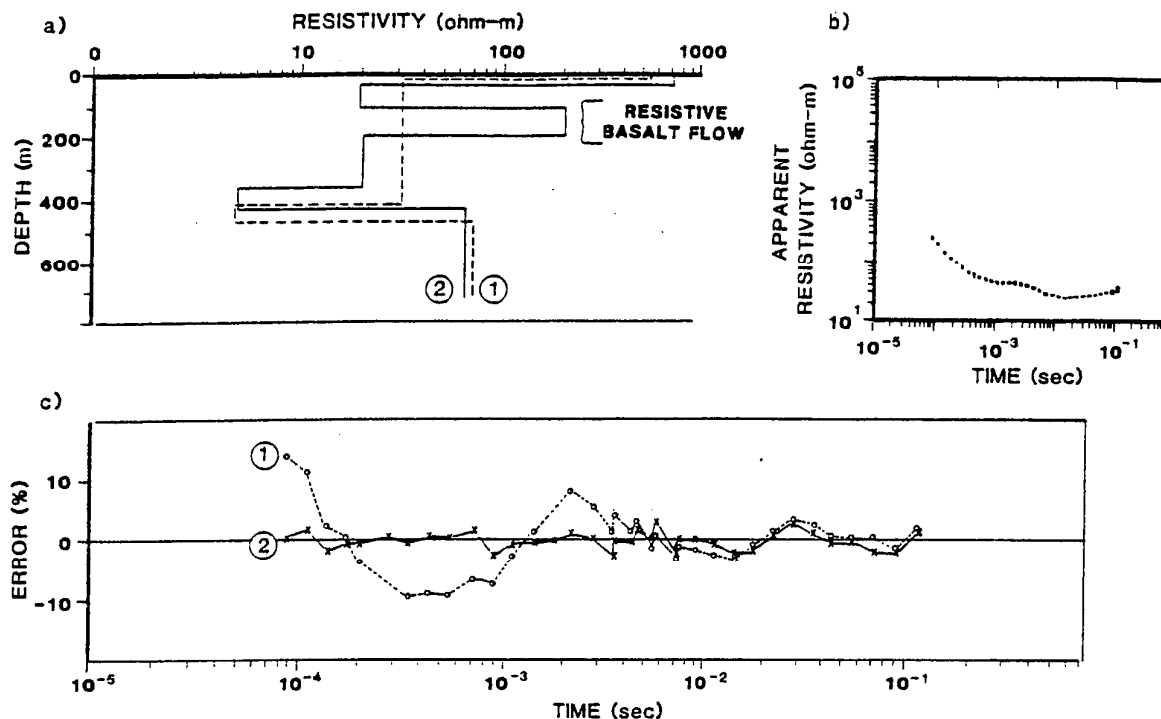


FIG. 7. Geoelectric sections (a) derived from 1-D inversions of measured apparent resistivity curve (b) over Tertiary Valley fill in Nevada. For each geoelectric section error of inversion is shown as function of time (c).

Validity of One-Dimensional Interpretation

The complexity of evaluating the influence of 2-D and 3-D structures of TDEM data is often cited as a disadvantage (Goldman, 1988). Indeed, currently, computations of 2-D and 3-D structures require computations that cannot be economically and practically applied in routine exploration programs. From the 2-D and 3-D computations (Newman et al., 1987) that have been published, important conclusions can be derived about the validity of 1-D interpretations in the presence of 2-D and 3-D structures. For example, Newman et al. (1987) computed the response over a resistive and conductive 3-D structure buried in a layered half-space at a depth of about 300 m. They reached the conclusion that 1-D inversions gave good estimates of the depth of burial of the 3-D structure, but unreliable depth extent and resistivities of the 3-D body. They used relatively large transmitter loops (1000 m by 1000 m) compared to exploration depth (1000 m) in their computations.

Drill-hole control is seldom sufficient to evaluate thoroughly the influence of 2-D and 3-D structures on a data set. Our experience, based on several thousand sound-

ings with transmitter loop dimensions varying from 30 m by 30 m to 500 m by 500 m, is that 1-D interpretations yield good depth interpretations in the vast majority of work undertaken. Nevertheless, practical algorithms for data interpretation in the presence of 2-D and 3-D structures is an important need in TDEM soundings. Some efforts in that direction are promising (James, 1988).

Case Histories

Case History—High Level Nuclear Waste Repository Siting

The storage panels of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico are being mined in the bedded salts of the Salado formation at a depth of about 600 m below ground surface. Underlying the Salado formation is the Castile formation, which is composed primarily of anhydrite and halite. It is known from oil and gas drilling that the Bell Canyon formation, underlying the Castile formation, can contain brines (Barrows et al., 1982).

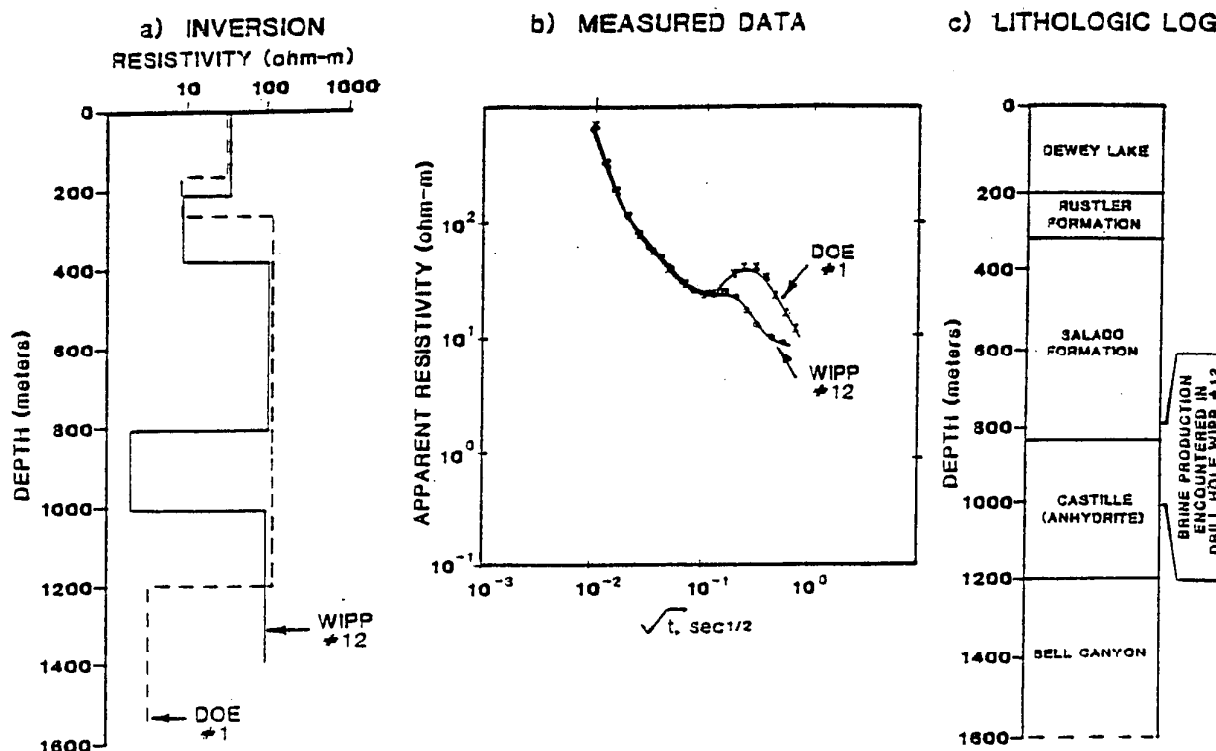


FIG. 8. Two measured late-stage apparent resistivity curves (b) and corresponding geoelectric sections derived from 1-D inversions (a). Also shown is a lithologic log common to both sounding locations (c).

The concept for placing a high level nuclear waste (HLW) repository in bedded salts at 600 m is to exploit the low hydraulic permeabilities of overlying bedded salts, and underlying anhydrites and halites. However, in the general vicinity of Carlsbad, New Mexico, drill holes encountered pressurized brine reservoirs at depths between 730 m and 915 m in the Castille formation (Register, 1981). The objective of TDEM surveys was to map the depth of first occurrence of brine over the waste storage panels and surrounding area.

A TDEM survey was conducted on a 500 m grid using central loop TDEM soundings over the waste storage panels and at selected drill hole locations. The transmitter loop dimensions employed were 500 m by 500 m and the TDEM equipment used was the Geonics EM-42.

Figure 8b shows two apparent resistivity curves located within 150 m of two drill hole locations, WIPP #12 and DOE #1. The resistivity layering derived from 1-D inversions for these two soundings is given in Figure 8a., and Figure 8c shows a lithologic log common to WIPP #12 and DOE #1. In the drilling of WIPP #12, brines were encountered at a depth of 850 m, and in drill hole DOE #1 no brines were encountered to total depth

(TD = 900 m). The depth of first occurrence of brine observed in WIPP #12 is in excellent agreement with the depth of the low resistivity layer derived from the 1-D inversion of the adjacent TDEM sounding. Depth of occurrence of the low resistivity layer derived from the TDEM inversion near drill hole DOE #1 is at 1200 m, some 300 m below TD, and at a depth corresponding to the Bell Canyon formation.

The 1-D inversions of TDEM soundings over the waste storage panels showed first depth of occurrence of brine below 1050 m. This depth generally corresponds to the Bell Canyon formation. Thus, the 1-D interpretations of the depth of first occurrence of brine were consistent with available ground truth. A major concern remains the minimum dimensions of brine occurrences detectable with central loop soundings. This problem is being addressed by 2-D and 3-D forward modeling.

There are several other important objectives in environmental geophysics for mapping depth of first occurrences of brine, such as:

- (1) Siting injection zones for oil field brines, and other liquid waste injection wells. Regulations require

injection zones to have a concentration of dissolved solids greater than 10 000 ppm and confining zones must separate US drinking water supplies (USDW) and injection zones (Federal Register, 1987).

- (2) Monitoring migration of wastes upward from injection zones along fractures, abandoned wells, or faulty casings (Fitterman et al., 1986).

Mapping Encroachment of Salt Water Into Fresh-Water Aquifers

Intrusion of salt water in coastal aquifers often has as its main cause excessive withdrawal of ground water. It has long been recognized that surface electrical or electromagnetic methods can be effective in mapping fresh water—salt water interfaces (Flathe, 1964). Here, the

application of TDEM surveys for this purpose is illustrated by a case history from the Salinas Valley, CA (Mills et al., 1988). A schematic hydrogeologic cross-section of the study area is given in Figure 9. There are four aquifer zones (1) a perched aquifer in which the ground water is heavily contaminated by fertilization, (2) a 180 ft aquifer approximately 60 m thick in which salt water has intruded under about 15 000 acres, (3) a 400 ft aquifer in which salt-water intrusion has been observed under about 6600 acres, and (4) a 900 ft aquifer in which no salt-water intrusion has yet been observed.

Thus, salt-water intrusion has progressed farthest inland into the 180 ft aquifer, so that to map water quality in the 400 ft aquifer requires exploration through a 180 ft aquifer containing high concentrations of dissolved solids. This information was used in designing the survey. To map salt-water encroachment in the 180 ft aquifer 100 m by 100 m transmitting loops were em-

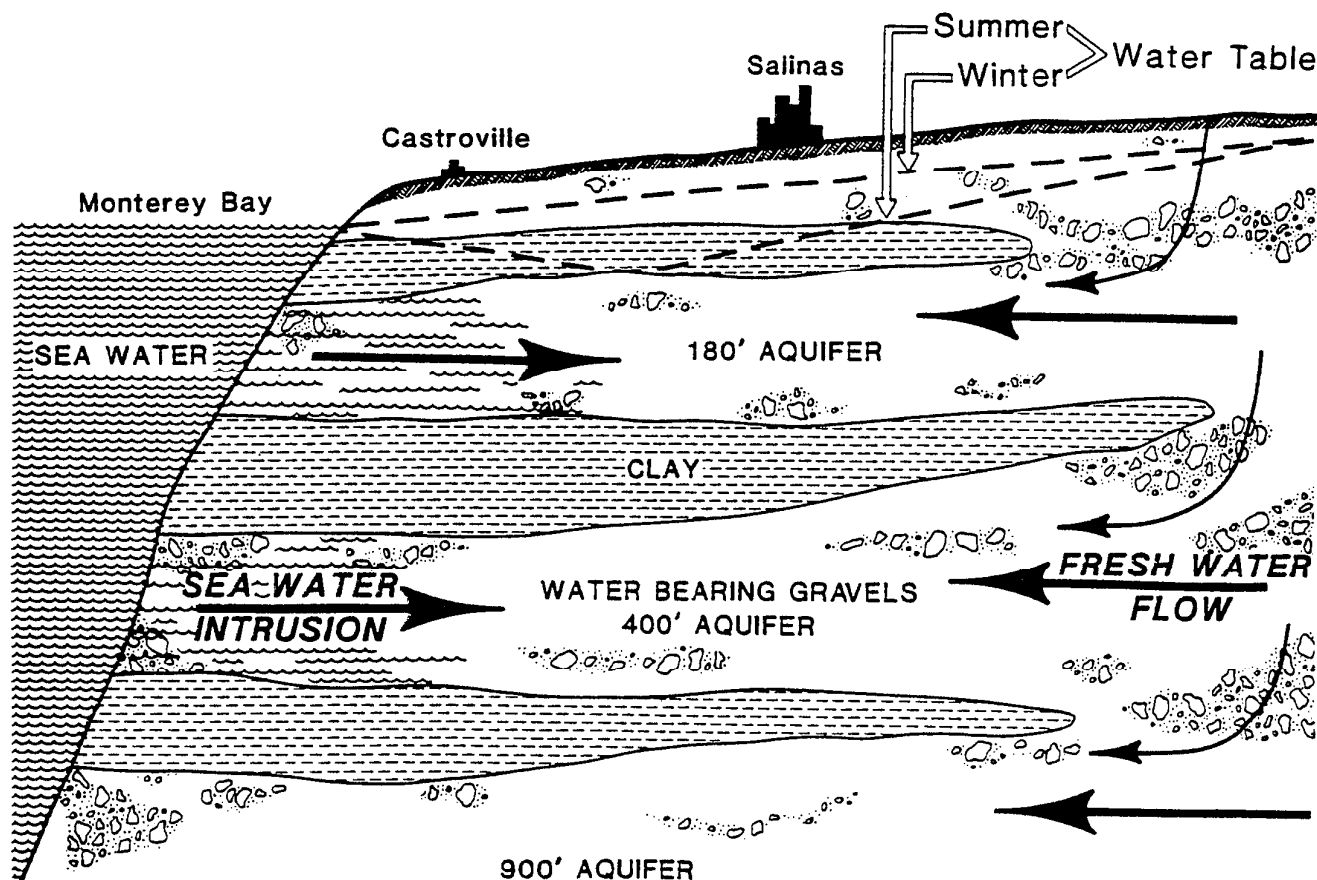


FIG. 9. Schematic hydrogeologic section of study area in the Salinas Valley, CA.

ployed. These transmitting loop dimensions provided sufficient field strength to derive the resistivity variation in the 180 ft aquifer. Larger transmitting loop dimensions (200 m by 200 m) were employed for exploration in the 400 ft aquifer. Approximately 100 stations were measured.

A series of four late-stage apparent-resistivity curves along cross-section B-B' (Figure 12) are shown on Figure 10 along with geoelectric sections derived from I-D inversions. Figure 11 shows the geoelectric section derived from TDEM soundings along profile B-B'. In the 180 ft aquifer the resistivity gradually increases inland from $1.5 \Omega \cdot \text{m}$ (station L24/3) to $18 \Omega \cdot \text{m}$ (station L10/1). In the 400-ft aquifer the resistivity increased from $6.0 \Omega \cdot \text{m}$ to in excess of $20 \Omega \cdot \text{m}$.

Information from monitoring wells maintained by the Monterey County Flood Control and Water Conservation

District was used to help constrain the number of layers used for the inversions of the TDEM data, and to correlate formation resistivities with equivalent chloride concentration. Correlation of formation resistivities with chloride concentration showed that a resistivity of approximately $8 \Omega \cdot \text{m}$ corresponds to a 500 ppm chloride concentration. Figure 12 shows the surface projection of the 500 ppm isochlor contours ($8 \Omega \cdot \text{m}$ formation resistivity) in the 180 ft and 400 ft aquifers. The 500 ppm isochlor, based on monitoring wells, is also shown. There is more detail in the contours derived from the TDEM surveys mainly because of the higher station density.

These types of TDEM surveys have now been performed in several areas of Florida (Steward and Gay, 1981), Massachusetts (Fitterman and Hoekstra, 1982), California (Mills et al., 1988), and New York. Important advantages of TDEM soundings in these surveys are:

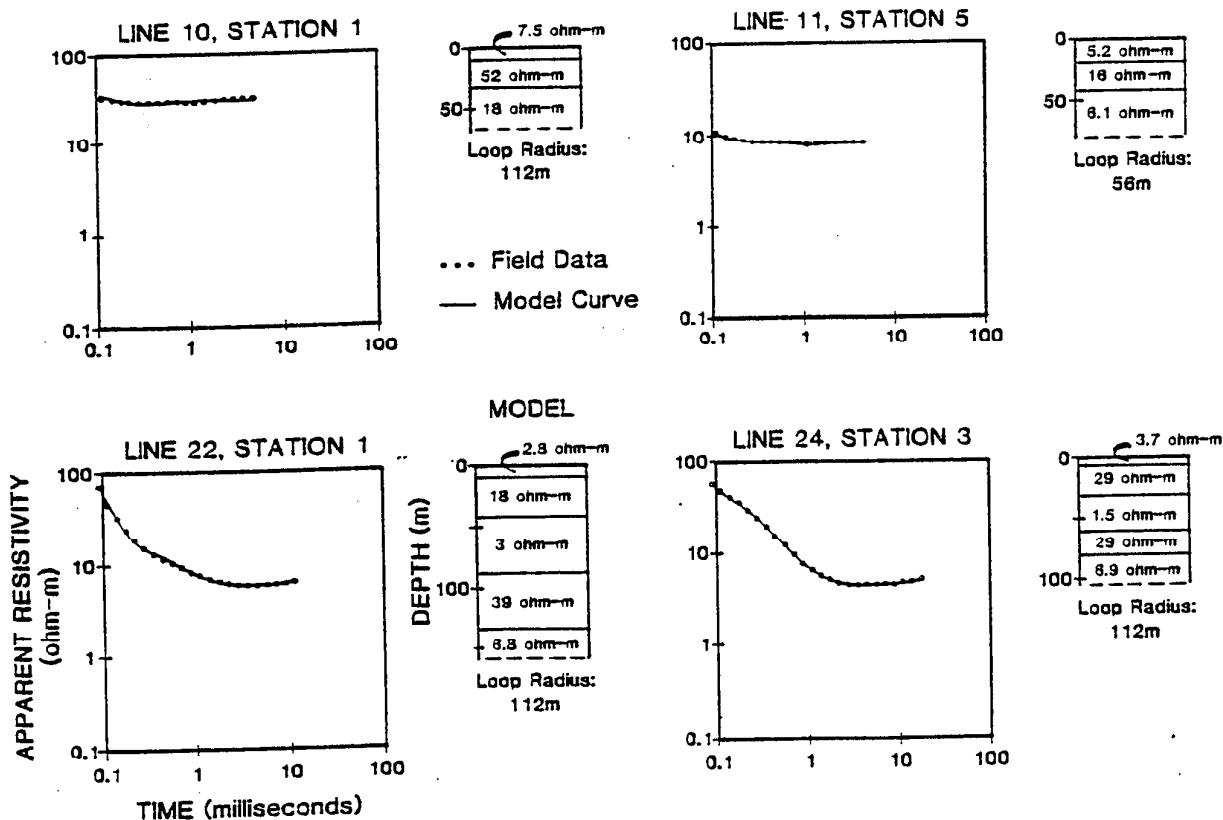


FIG. 10. Four apparent resistivity curves and inverted geoelectric sections along section B-B' (Figure 12).

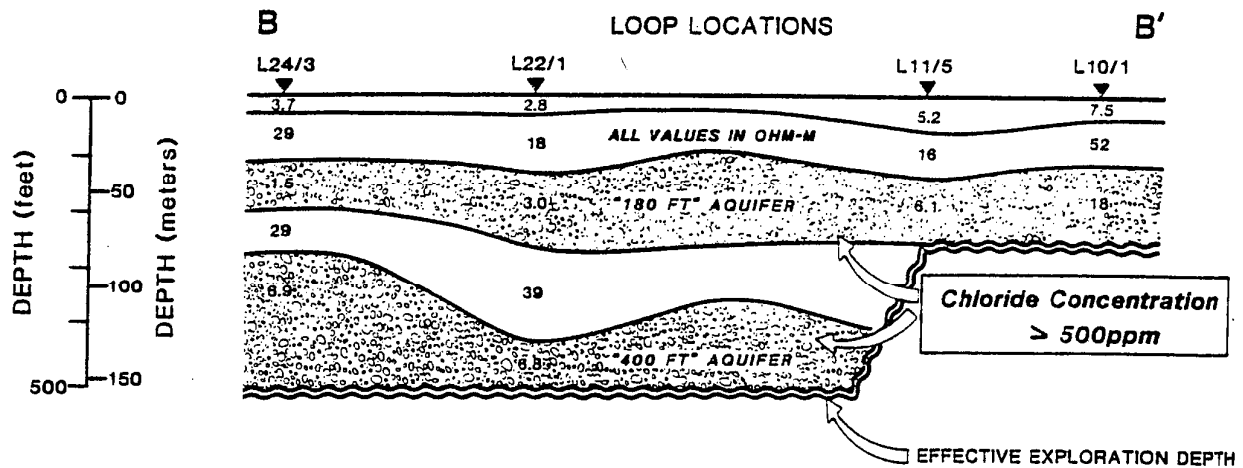


FIG. 11. Geoelectric section B-B' derived from TDEM soundings.

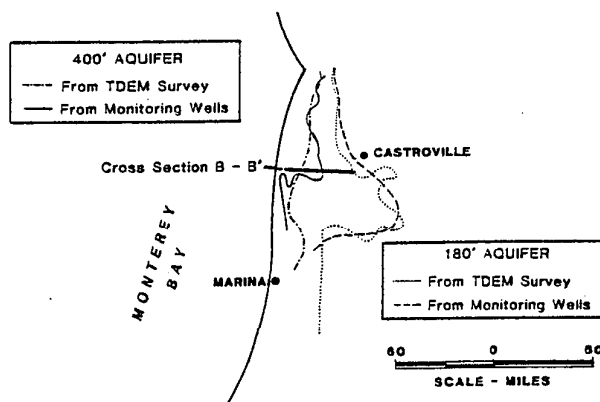


FIG. 12. Comparison of position of 500 ppm isochlor in 180 ft and 400 ft aquifers derived from monitoring wells and TDEM soundings.

- (1) Coastal areas are often urbanized and limited space is available for measurements. TDEM measurements were often made in available open spaces such as high school athletic fields and parks.
- (2) Ambient electrical noise (e.g., powerlines and radio stations) is high in developed areas. The signal stacking used in TDEM has proven an effective way for recovering signal from noise.

The utility of TDEM surveys for water management plans are in (1) providing optimum location for place-

ment of monitoring and production wells, (2) determining depth of completion of such wells, (3) interpolating the position of the fresh water-saline water interface between wells, and (4) monitoring the movement of the interface over time. Geophysical stations can be moved from year to year, while monitoring wells lose some of their usefulness once the fresh water-saline water interface has migrated past their locations.

Shallow TDEM Surveys

Important exploration objectives for shallow (< 50 m) electrical exploration in environmental geophysics are

mapping continuity of confining layers, such as clay lenses;

mapping the presence of contaminants (e.g., originating from brine ponds) and pathways for migration of contaminants, such as fractures and shear zones;

correlating hydraulic transmissivities to electrical conductance (e.g., Huntley, 1986).

The geophysical methodologies applied to these exploration problems have mainly been dc resistivity soundings (e.g., Evans et al., 1982) and frequency-domain electromagnetic conductivity profiling (e.g., McNeill, 1982). With the recent availability of a TDEM system (Geonics EM-47) for shallow exploration, some of these objectives are now within the exploration depth range of TDEM. An example of shallow central-loop soundings with a prototype EM-47 is a survey over relatively thin basalt flows near Golden, Colorado.

On North and South Table Mountain in Golden, Colorado, lava flows overlie the Denver formation. Figure 13a shows the geologic section of the upper 100 m on North Table Mountain (Waldschmidt, 1939). Figure 13c shows an apparent resistivity curve measured in the center of a 30 m by 30 m transmitter loop with the EM-47 and its 1-D inversion. A peak current of 2 A was driven through the loop, and the ramp turn-off (Figure 4a) was $2.5 \mu\text{s}$. The first time gate was centered at $6.4 \mu\text{s}$ and data were collected at base frequencies of 300 Hz and

30 Hz. The geoelectric section derived from the 1-D inversion (Figure 13b) shows good agreement between geologic boundaries and breaks in resistivity.

For this geoelectric section and for 30 m by 30 m transmitter loops ($R = 15 \text{ m}$), late stage commences at about 10^{-5} s (Figure 3), so that almost the entire measured curve is in late-stage. Also shown on Figure 13c are forward modeled curves with different thicknesses of the upper basalt flow, while all other parameters were held constant. Large changes in the curves occur mainly

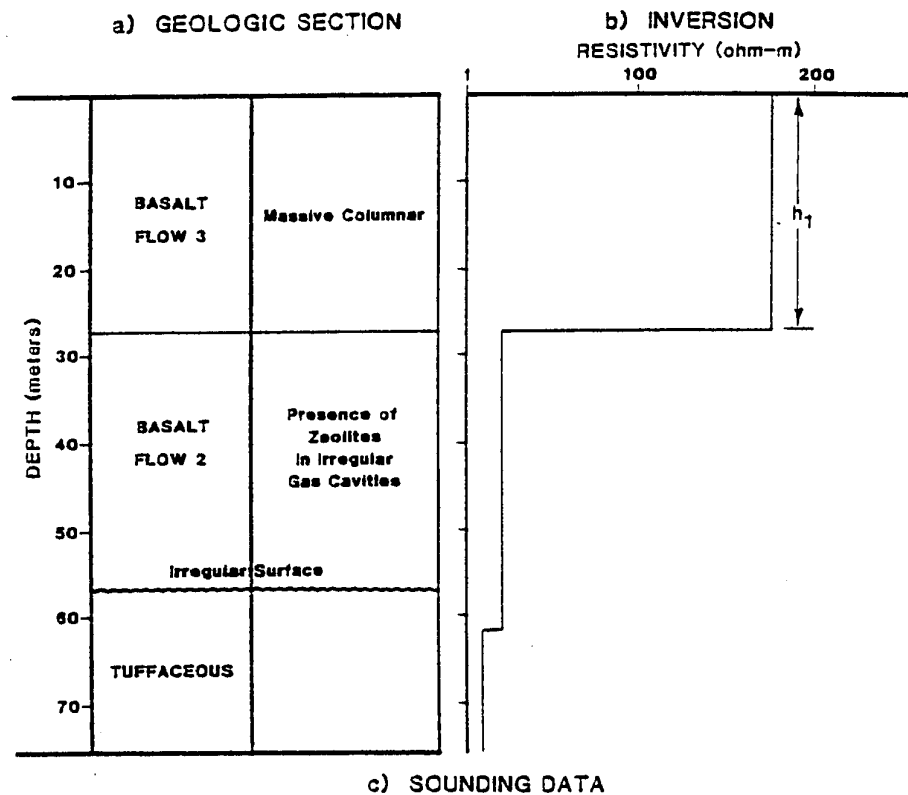


FIG. 13. (a) Geologic section of North Table Mountain, Golden, CO; (b); and geoelectric section derived from 1-D inversion of central loop sounding data with 30 m by 30 m transmitter loop; (c) the measured apparent resistivities are superimposed on a series of forward model curves in which the thickness of the upper basalt layer is varied.

over the time range from 10^{-5} s to 10^{-3} s; the time range covered by EM-47 measurements.

The conclusions from a number of conducted surveys is that the EM-47 can be employed in the depth range from 5 m to 75 m, depending somewhat on the geoelectric section. Since transmitter loop dimensions of 30 m by 30 m can be employed, survey productivity is high (30 to 50 stations per day). The TDEM EM-47 promises to be an effective methodology for electrical mapping in environmental geophysics, particularly in urban areas where space is limited and ambient noise is high.

Discussion

Focusing on the use of TDEM methods in environmental geophysics is such a narrow focus that there is a danger of overstating the utility of TDEM, compared to other electrical and electromagnetic measurement techniques. Raiche et al. (1985) and Fitterman et al. (1988) show that the range of equivalence in some geoelectric sections can in principle be reduced by combined use of dc resistivity and TDEM soundings. It is, therefore, important to note that the exploration objective in all three case histories consisted of determining depth to a conductive stratum, objectives optimally suited for electromagnetic techniques. TDEM surveys and other electromagnetic techniques have limitations for detecting thin resistive strata, and such limitations are readily evaluated by forward modeling.

One advantage of TDEM not evident from forward modeling computations is the absence of scatter in the data. The data scatter frequently observed in dc resistivity soundings, and distant source techniques (controlled source audiomagnetotelluric, audiomagnetotelluric, and magnetotelluric methods) are often due to lateral variation in resistivity and measurement of the electric field. The scatter is reduced in central loop TDEM soundings mainly because of the short source/receiver separation and measurement of the time derivative of magnetic fields. The apparent resistivity curves shown in these investigations are typical of a large number of stations. No smoothing of the data is performed before inversions.

The recent availability of a shallow TDEM system for the exploration depth range from 5 m to 75 m makes this technique suitable for such environmental studies as well-site protection programs, and mapping plumes of ground-water contamination. Contamination plumes are often confined to narrow zones, and the high lateral resolution possible with shallow central loop TDEM soundings allows definition of both the lateral and vertical extent of such plumes.

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